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SYSTEMS ANALYSIS DIVISION

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WEATHER ASPECTS OF THE SONIC BOOM

May 1960

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[illegible] ASPECTS OF THE SONIC BOOM

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ABSTRACT

An explanation of the effect of meteorological conditions on the path of the sonic boom is presented. Areas covered by sonic booms resulting from aircraft flying at various Mach numbers and dive angles are shown, taking standard atmospheric gradients into account. Calculations are given for the effect of the jet stream as well as ordinary winds on the sonic boom.

I. INTRODUCTION

Observations have shown that meteorological conditions modify the path of sound and shock waves, sometimes to a considerable extent. Acoustic theory has been successfully applied to determine where the blast waves from large explosions will strike, Reference (1). More recently this theory has been applied to sonic booms by British investigators, Reference (2). The object of this report is to present briefly the physical principles which are involved. These principles are applied to determine the areas covered by sonic booms generated by aircraft flying at various altitudes, Mach numbers, and dive angles, taking the standard atmospheric gradients into account; that is, modifications to Reference (3) which treats only the homogenous atmosphere. In addition, the significant effect of ordinary winds as well as the jet stream on the path of a sonic boom is presented.

II. ANALYSIS

The major elements of weather affecting the path of sound rays or rays of the weak shock waves which constitute the sonic boom are the vertical gradients of temperature and wind.

The immediate effect of temperature is to change the speed of the ray and consequently, as will be shown, its direction. The relationship of the speed of sound to temperature, Reference (1), is given by

$$c = 38.98\, K^{\frac{1}{2}} \qquad (1)$$

where c = speed of sound in knots

K = temperature in degrees Kelvin.

The correction to speed of the sound because of humidity may be calculated by a formula of Reference (4).

A useful approximation to the vertical gradient of the speed of sound for the standard atmosphere is given by

$$c = c_g - \alpha z \qquad 0 \leq z \leq 5.81 \qquad (2a)$$

$$c = c_g - 5.81K \qquad z > 5.81 \qquad (2b)$$

where c_g = speed of sound on the ground, knots

α = 1[illegible].[illegible]5 knots per nautical mile altitude

z = height above ground in nautical miles

The constant 5.81 nautical miles corresponds to 35,330 feet of the ICAO atmosphere.

In order to simplify the analysis, the effect of temperature gradient with no wind is considered first and followed by the case where, in addition to the temperature gradient, a vertical wind gradient exists.

A. Effect of Temperature Gradient (Zero Wind)

The changes in direction of a ray as it enters a medium with a different sound speed is governed by Snell's law which may be written as

$$\sin \varphi = \frac{c}{c_i} \sin \varphi_i = \frac{c}{A} \qquad (3)$$

where φ_i = the angle a ray makes with the normal in the reference region of air

c_i = speed of sound in the reference region

φ = the angle a ray makes with the normal in an arbitrary air region

c = speed of sound in an arbitrary air region

A = $c_i \csc \varphi_i$ = constant

If one takes as the reference region, the region where a sonic boom originates, φ_i = Mach angle, so that $A = M c_i$, where M is the Mach number.

As in optics one may draw the following conclusions from equation (3): (1) as c decreases, the angle φ which the ray makes with the normal decreases, so that the ray is bent towards the normal; (2) conversely,

as c increases, the ray is turned away from the normal; (3) as c increases so that the absolute value of c/A passes through unity, total reflection will occur; (4) if the value of φ is zero no refraction will occur.

The displacement y along the projection of the line of flight, at an altitude z is found from the relations

$$y = z \tan \varphi_i \qquad z > 5.81 \tag{4a}$$

$$\frac{dy}{dz} = \tan \varphi \qquad 0 \leq z \leq 5.81 \tag{4b}$$

and equations (2) and (3) giving

$$y = (h-5.81) \tan \varphi_i + \frac{1}{k}\left\{\left[A^2 - (575.4)^2\right]^{\frac{1}{2}} - \left[A^2 - (c_g - kz)^2\right]^{\frac{1}{2}}\right\} \qquad z > 5.81 \tag{5a}$$

$$y = \frac{1}{k}\left\{\left[A^2 - c_i^2\right]^{\frac{1}{2}} - \left[A^2 - (c - kz)^2\right]^{\frac{1}{2}}\right\} \qquad 0 \leq z \leq 5.81 \tag{5b}$$

where h = altitude at which sonic boom originates in nautical miles. The origin of the coordinate system is chosen on the ground directly below the point where the sonic boom originates.

From equations (5) one sees that in the isothermal region of the standard atmosphere the rays will be simply straight lines and below the isothermal region the rays will follow circular paths. Paths of such rays are shown in Figures (1) and (2). Due to the convenience of choosing different units for abscissa and ordinate the paths do not appear circular.

In order to determine the effect of the standard atmosphere on the area covered by a sonic boom one first examines the cone of rays formed when a sonic boom is generated. In Figure (3), a sketch of the geometry is shown. In an isothermal atmosphere a ray originating at A making a Mach angle φ_i with the vertical would intersect the ground at the point B. Due to the standard atmospheric gradient the point B will be displaced to the point B'. The displacement 0 B' is found by equation (5). To find the angle i, that is, the angle a plane thru A B and the vertical axis makes with the vertical plane thru the "y" axis, one notes that

$$\tan i = \frac{x_o}{y_o} \qquad (6a)$$

$$y_o = s\,\frac{\sin \varphi_i}{\cos \gamma} - h \tan\gamma \qquad (6b)$$

$$x_o = (s^2 - y_o^2 - h^2)^{\frac{1}{2}} \qquad (6c)$$

where x_o and y_o are the lateral and horizontal displacements for the isothermal conditions, and,

φ_i = Mach angle

γ = dive angle of the aircraft

S = length of isothermal ray from A to ground.

Then the lateral displacement is given by the expression X = 0 B' sin i, and the displacement along the track by y = 0 B' cos i.

To this point the analysis considers the displacement of the sonic boom on the ground as a result of the atmospheric temperature gradient. No attempt is made to calculate the effect on the pressure level. For completeness, the pressure distribution on the ground for a M = 1.05 aircraft at several altitudes (60 degree dive) in an isothermal atmosphere is shown in Figure 4. This figure is reproduced from Reference (3). With the aid of the above analysis, the effect of a standard atmospheric gradient on the ground location of a sonic boom produced by an aircraft has been computed. The flight conditions selected for the computations here are identical to those used in Reference (3). The reason for this selection is that the reader can readily see the modifications produced by a real atmosphere to the sonic boom patterns of an isothermal atmosphere. The graphic results of the present calculations are shown in Figures 5 - 22 and, the results for the isothermal atmosphere are reproduced in Figures 5A - 22A as overlays.

B. Effect of Wind

The path of a ray in a real atmosphere where wind and temperature gradients exist is more complicated than where temperature gradients alone exist. The simple optical analogy no longer holds. The ray is no longer normal to the wave front and suffers a displacement due to the wind vector. By Huygen's principle, see for example Reference (5), it may be shown that

$$\tan \phi = \tan \theta + \frac{u}{c} \sec \theta \tag{7a}$$

$$\sin \Theta = \frac{c \sin \Theta_i}{c_i + \sin \Theta_i (u_i - u)} = \frac{c}{A-u} \qquad (7b)$$

where $A = c_i \csc \Theta_i + u_i = \text{const.}$

ϕ = angle a ray makes with the normal axis

Θ = angle the wave makes with the horizontal axis

u = horizontal component of the wind in the direction of the horizontal component of the ray

The subscript "i" refers to the region of reference (i.e. for the sonic boom the altitude at which it originates). Also with reference to the sonic boom, Θ_i equals the Mach angle.

For zero wind gradient, equations (7) reduce the Snell's law discussed above. From equation (7b), one sees that total reflection occurs when the absolute value of the right side of the equation increases and passes through unity. However, the deviation of the ray from the normal now depends on the ratio of the wind to the speed of sound.

If Θ_i and Θ are close to 90^0, i.e. for the case of almost glancing incidence, a useful approximation for estimating the effect of wind is given in Reference (1) by the expressions

$$\tan \phi = \tan \Theta \qquad (8a)$$

$$\sin \Theta = \frac{c+u}{A} \qquad (8b)$$

The horizontal displacement y relative to the origin can be found from integral $y = \int_h^z \tan \phi \, dz$ (9a)

Since in equations (7) the wind and sound speed depend on the altitude one may set

$$\tan \phi = \frac{c}{\left[(A-u)^2 - c^2\right]^{\frac{1}{2}}} + \frac{u\left[(A-u)^2 - c^2\right]^{\frac{1}{2}}}{c\,(A-u)} = f\,(z) \quad (9b)$$

and substituting into equation (9a)

$$y = \int_h^z f\,(z)\,dz \quad (9c)$$

The approximation by equations (8) lead to analytic solutions of the form given by equation (5).

For a real atmosphere, numerical methods of integration are required to find the path of a ray from equation (9c). Usually the quantities u and c entering into the function f (z) are derived from meteorological observations or predictions of wind, temperature and humidity at specified altitudes. Intermediate values of u and c at other altitudes may be found by interpolation from the given data. For sonic boom calculations it is usually adequate to evaluate the function f (z) at 1000' intervals and to apply Simpson's rule of integration. Sometimes the function of f (z) may become difficult to evaluate accurately in a certain region due to the quantities A-u approaching c in value. In that case, one notes from equation (7b), that this is the case of glancing incidence and consequently equations (8) may be used to get an analytical solution for the region in question. The graphic results of several wind profiles are shown in figures 1, 2 and 23.for both the standard temperature gradient and isothermal atmosphere and for a variety of Mach numbers, altitudes and dive angles.

III. DISCUSSION

The effect of a standard temperature gradient, considered alone, on a sonic boom produced by an aircraft is to alter the ground pattern from that expected for an isothermal atmosphere. The effect differs considerably for the flight conditions of the aircraft. At the lowest aircraft speed considered here, M = 1.05, the patterns are displaced in the forward direction and, extended in the lateral direction. For the 45° dive angle case at M = 1.05, the effect of temperature is to distend the pattern sufficiently so that, for an altitude of 40,000 ft. the pattern is open in the forward direction. At higher speeds, the primary effect is to limit the coverage of the sonic boom on the ground; that is for most flight conditions, the temperature gradient produces a closed figure whereas for the isothermal atmosphere the patterns are essentially parabolic. For the case where the aircraft makes a vertical dive, the circular pattern remains unchanged, however, the area covered by the boom is enlarged as a result of a temperature gradient.

The effect of wind depends on the ratio u/c; that is, the relative strength of the wind to the sonic ray. When the ratio is much less than unity, the effect of the wind is small, however, under certain conditions the effect of a wind gradient can be significant, when considered in conjunction with a temperature gradient. In Figure 1, the results for an isothermal atmosphere and standard temperature gradient are shown.

For an aircraft in level flight at an altitude of 20,000 feet and a Mach number = 1.05, the effect of the real atmosphere is to deflect the sonic boom from the ground. If, however, a wind profile exists, like the one shown, the rays will be deflected back to the ground. A similar effect is shown in Figure 2. Here, the wind profile has a shear or change of direction at 11,000 feet. When the wind is in the same direction as the ray the deflection is increased; however, below 11,000 feet with the wind in the opposite direction, the ray is deflected sufficiently so that it now touches the ground.

In Figure 23, the results are presented for a high altitude jet stream. (The wind profile presented is a recommended standard for aircraft design by the U. S. Air Force.) The high velocity wind of the jet stream produces a major effect on the displacement of the sonic boom; almost a factor of two, about 8.5 miles vs. 13.8 miles. If the wind direction is opposite to the ray direction, the boom would be displaced to the left of the no wind curve on the chart.

IV. CONCLUSIONS

1. Correct prediction of the occurence of sonic booms requires incorporation of primary atmospheric effects, temperature and wind.

2. When standard temperature gradients are considered alone, the variations in ground coverage area of the sonic boom are functions of aircraft speed, aircraft altitude and angle of aircraft trajectory (dive angle). In general, the initial point of the sonic boom is projected somewhat forward of and the lateral spread is greater than for a homogenous atmosphere. A more significant effect occurs for speeds greater than M = 1.5; whereas for the homogenous atmosphere the shape is parabolic (open ended) the area covered by the sonic boom in a standard atmosphere is a closed figure, compare Figures 13 and 13A.

3. The effect of a vertical wind vector profile on the path of a shock ray can be pronounced; that is, offset the effect of the temperature gradient or accentuate it, as shown in Figures 1 and 2 respectively.

4. In the event a high wind, like the jet stream, exists aloft it can displace the initial point of the sonic bang by several miles, see Figure 24.

5. In the case of a cross-wind profile, the patterns shown in Figures 5 - 22 can be displaced above or below the horizontal axis.

SYMBOLS

c	speed of sound at any altitude
c_g	speed of sound on the ground
c_i	speed of sound at altitude of reference
h	altitude of aircraft
i	angle that the plane thru an isothermal ray and the vertical axis, makes with the vertical plane
k	gradient of speed of sound with altitude
s	length of an isothermal ray
u	component of wind along horizontal axis in the place of the line of flight
u_i	component of wind along horizontal axis in the plane of the line of flight at reference altitude
x y z	coordinates of a point for which the XY plane is the horizontal and the YZ plane the vertical
x_o y_o	coordinates of conic section determined by the horizontal plane and the cone of isothermal rays
A	constant appearing in Snell's law, as well as when speed of wind is considered.
K	temperature in degrees Kelvin
M	Mach number of airplane
γ	dive angle of airplane
θ	angle the sound or shock wave makes with the horizontal axis
ϕ	angle that a ray makes with the normal
ϕ_i	angle that the ray makes with the normal at the reference altitude

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3. "Review of Sonic Booms" - Fisher, D. - Navy Dept - BuAer - Research Division Report No. DR-1742 - October 1957
4. "Sound Propagation in the Atmosphere" - B. Gutenberg - Compendium of Meteorology - American Meteorology Society - Boston, Mass - 1951
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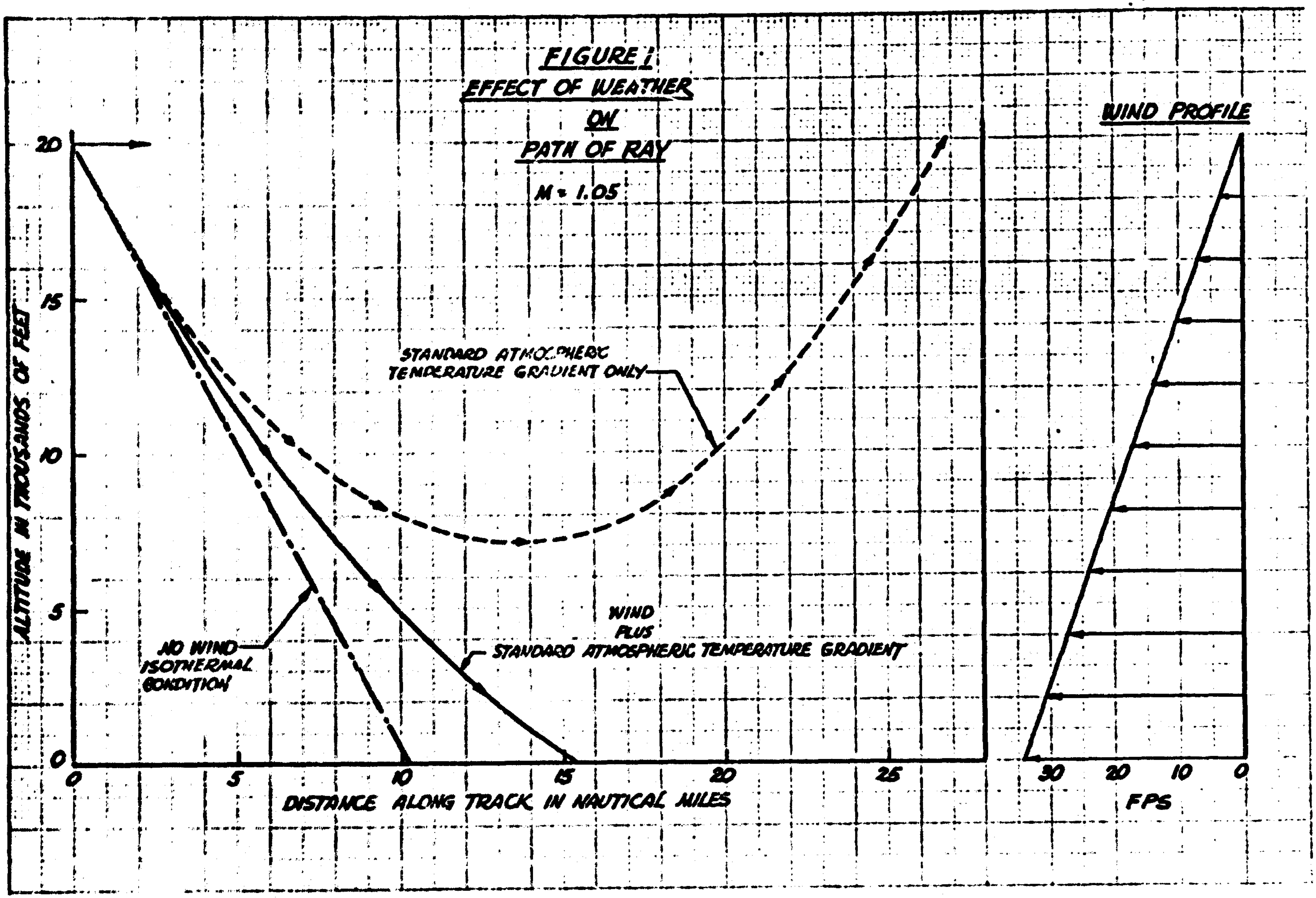


FIGURE I
EFFECT OF WEATHER
ON
PATH OF RAY
M = 1.05
STANDARD ATMOSPHERIC
TEMPERATURE GRADIENT ONLY
WIND
PLUS
STANDARD ATMOSPHERIC TEMPERATURE GRADIENT
NO WIND
ISOTHERMAL
CONDITION
ALTITUDE IN THOUSANDS OF FEET
20
15
10
5
0
0
5
10
15
20
25
DISTANCE ALONG TRACK IN NAUTICAL MILES
WIND PROFILE
30
20
10
0
FPS

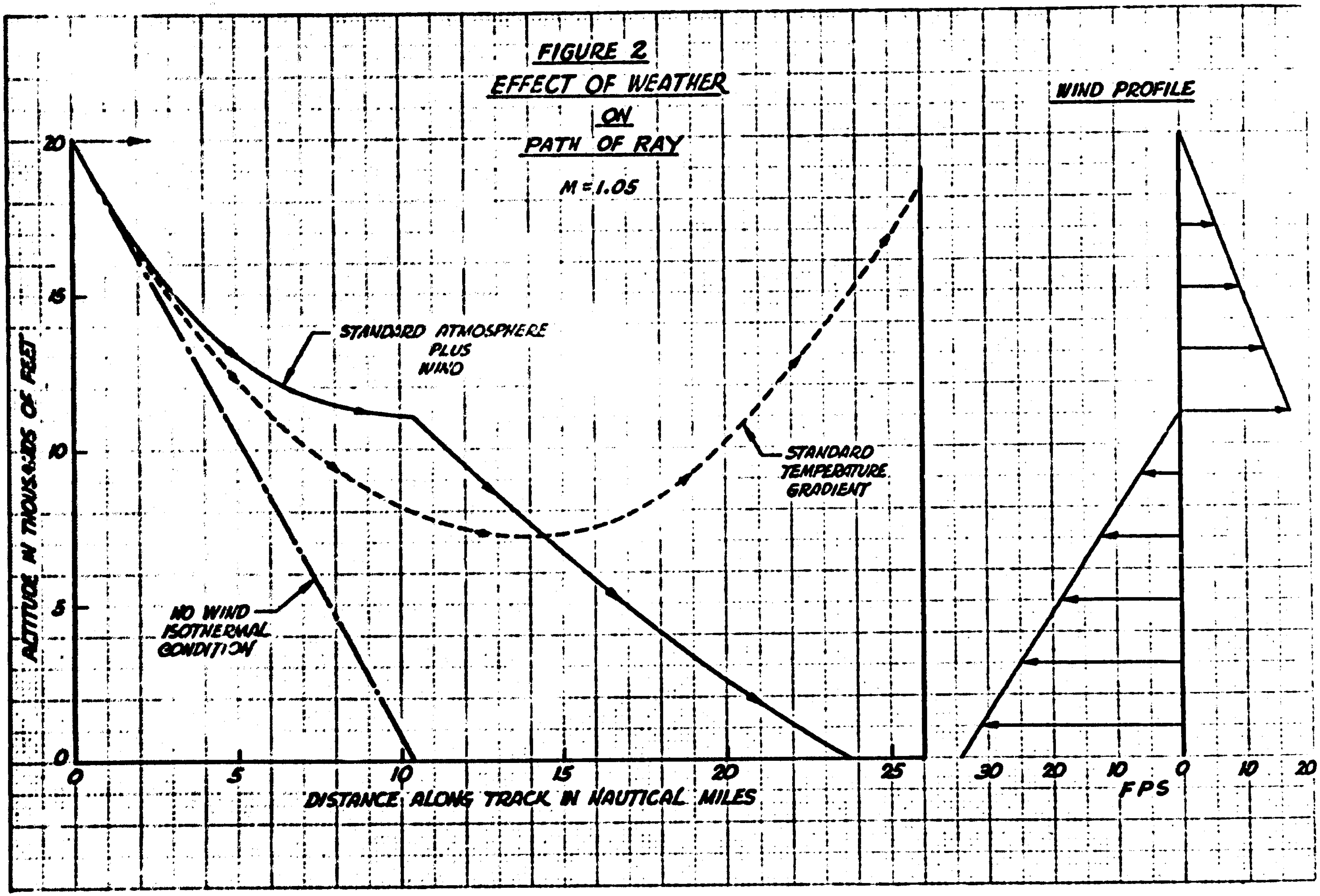


FIGURE 2
EFFECT OF WEATHER
ON
PATH OF RAY
M = 1.05
WIND PROFILE
STANDARD ATMOSPHERE
PLUS
WIND
STANDARD
TEMPERATURE
GRADIENT
NO WIND
ISOTHERMAL
CONDITION
ALTITUDE IN THOUSANDS OF FEET
20
15
10
5
0
0
5
10
15
20
25
DISTANCE ALONG TRACK IN NAUTICAL MILES
30
20
10
0
10
20
FPS

FIGURE 3
TYPICAL GEOMETRY
FOR
CALCULATING THE TRACE OF A RAY

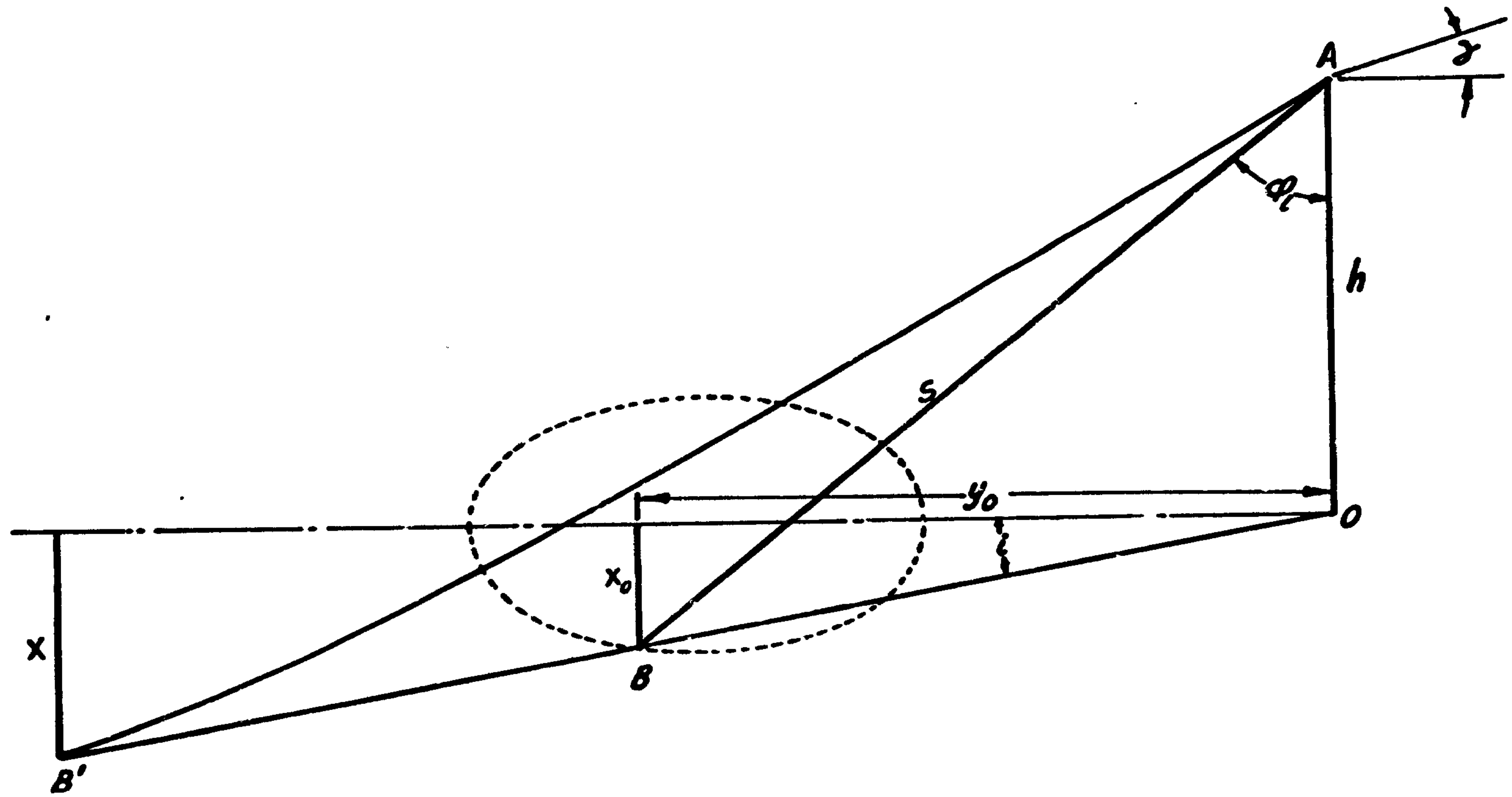
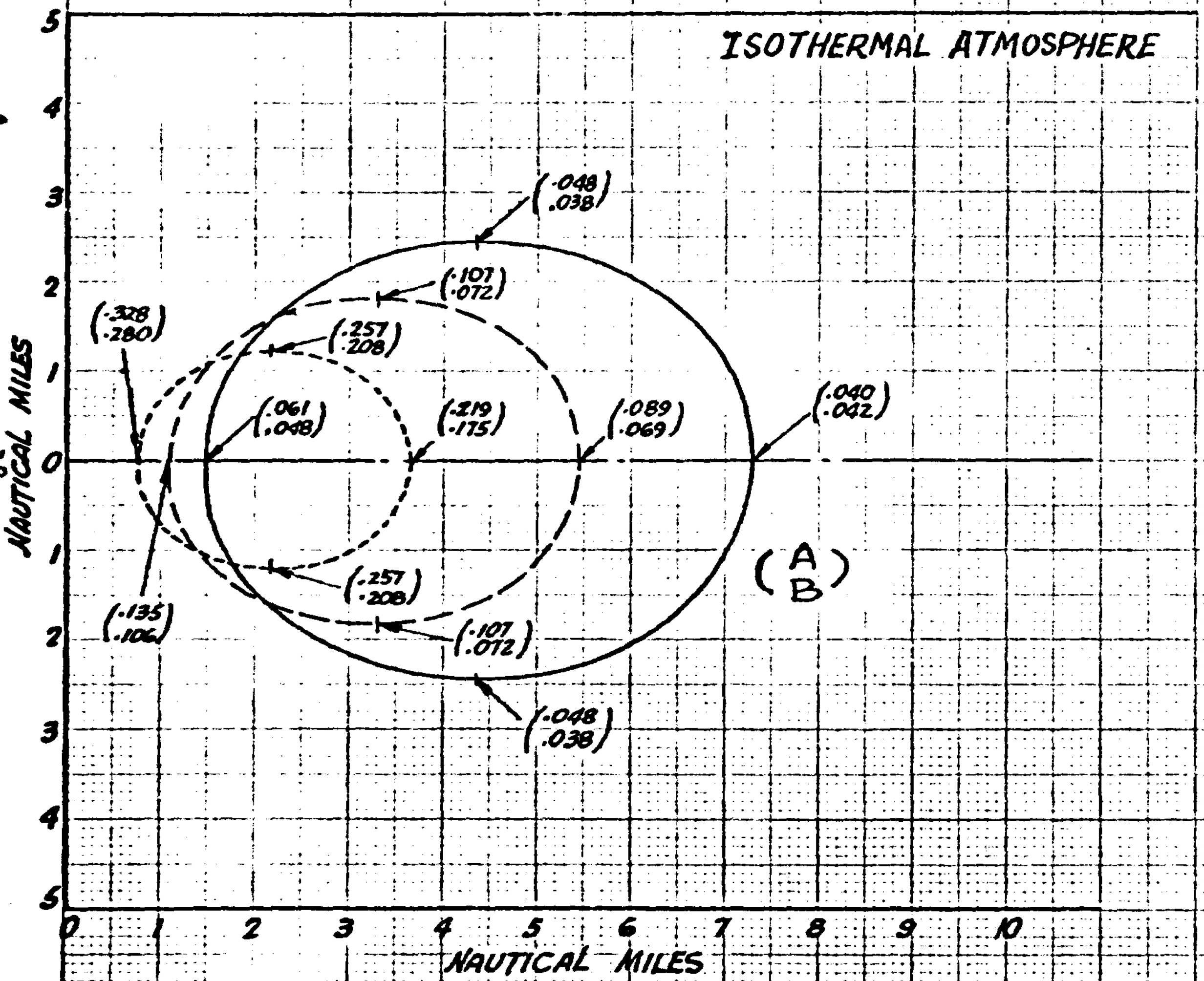


FIGURE 4

GROUND PRESSURE FROM SONIC BOOM

MACH NO. = 1.05 DIVE ANGLE = 60°



ALTITUDE

40,000'

30,000'

20,000'

O - Aircraft directly above this point

A - $P/\delta l^{3/4}$ for "1g" deceleration

B - $P/\delta l^{3/4}$ for "1g" acceleration

P - Overpressure in pounds per square foo

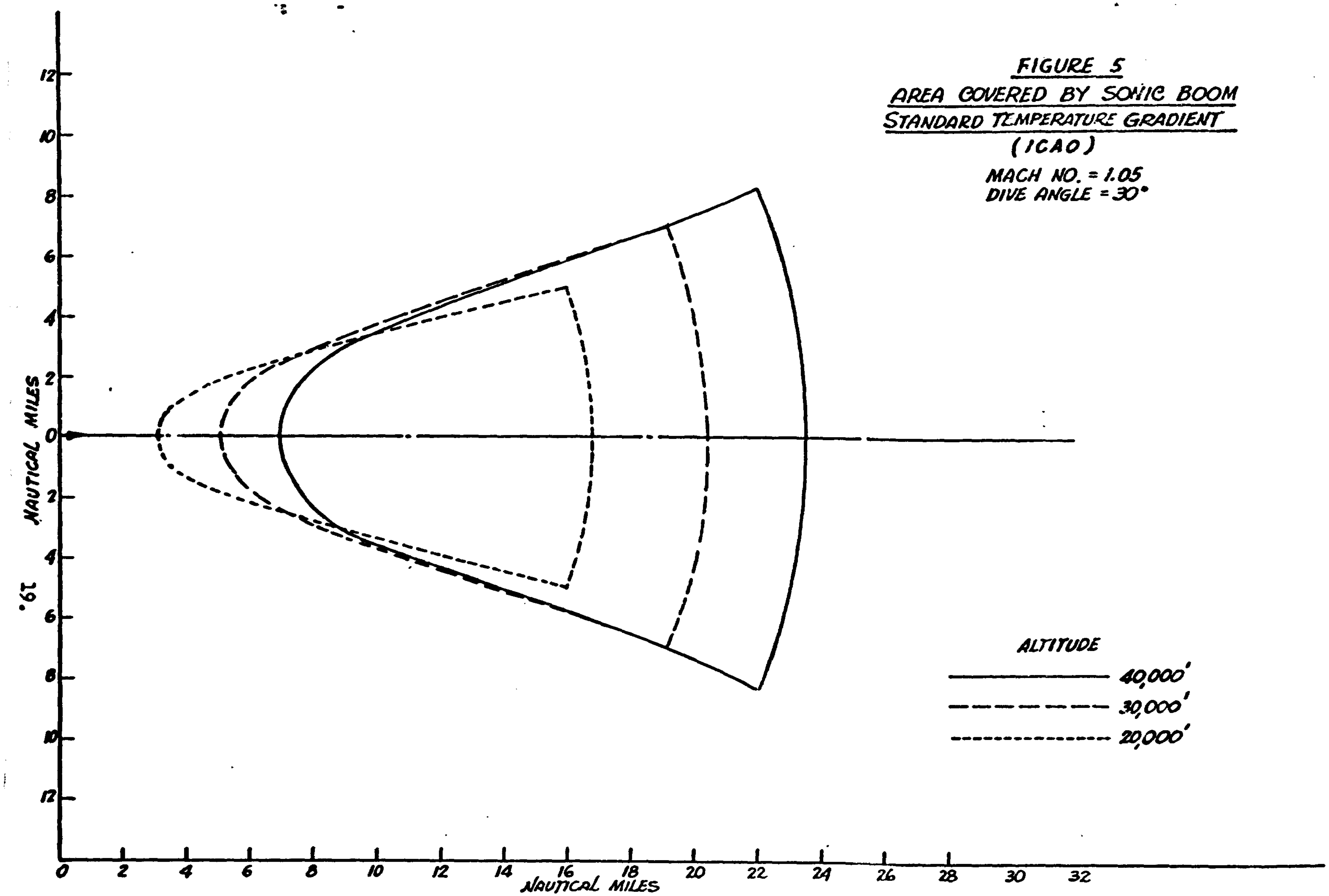
aircraft form parameter

δ - Diameter to length ratio of aircraft

l - Length of aircraft in feet

FIGURE 5
AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE GRADIENT
(ICAO)

MACH NO. = 1.05
DIVE ANGLE = 30°



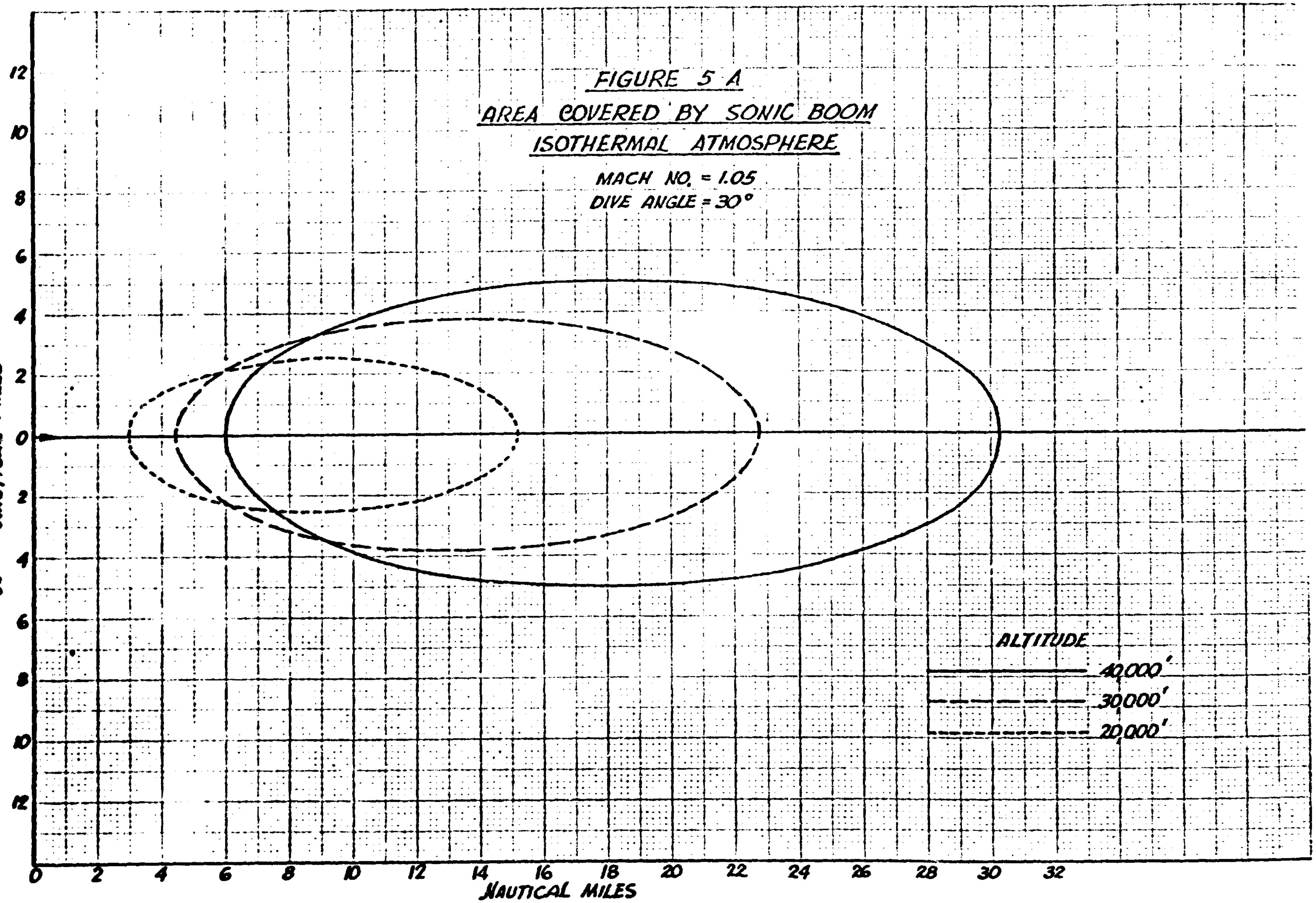
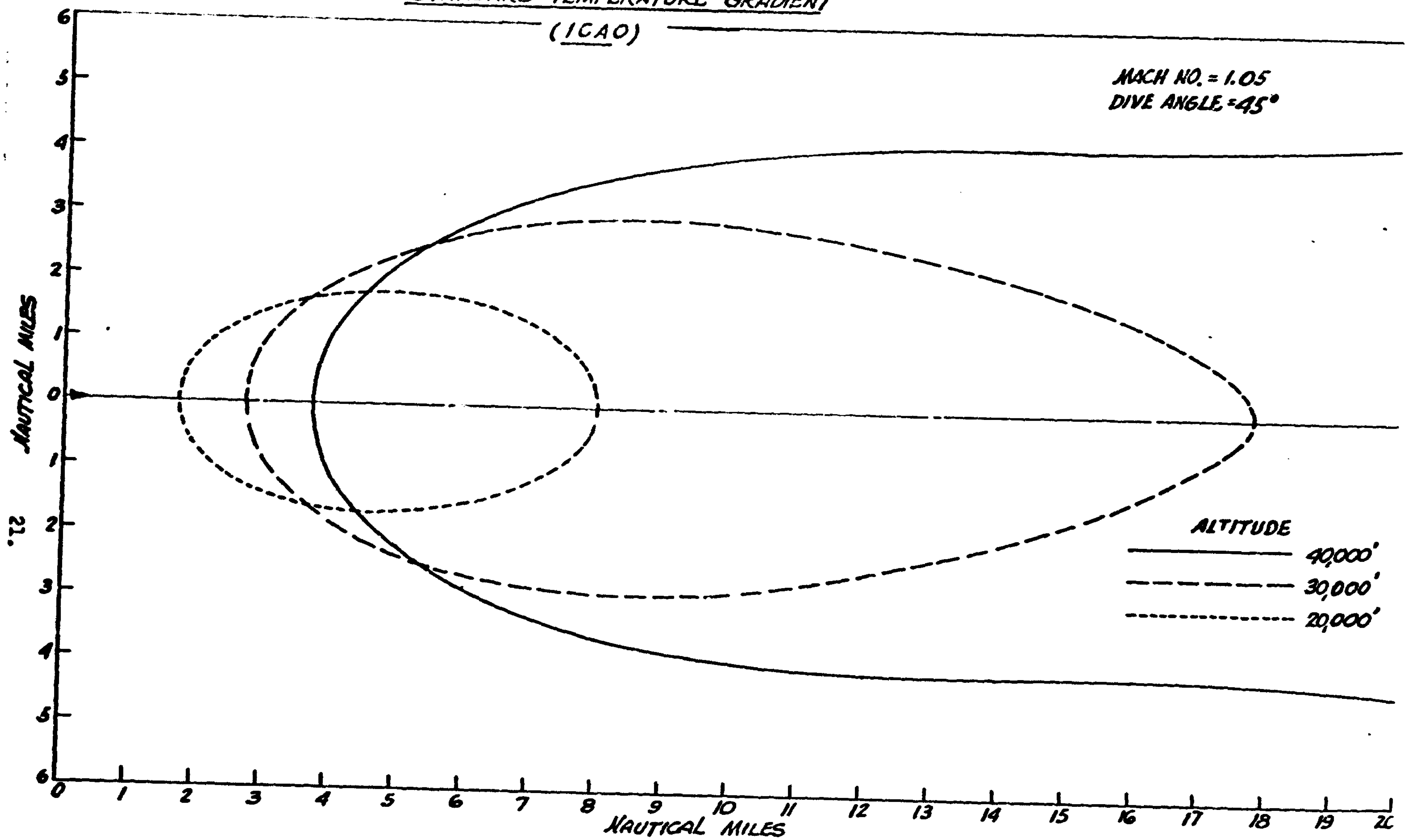


FIGURE 5 A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 1.05
DIVE ANGLE = 30°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
12 10 8 6 4 2 0 2 4 6 8 10 12

FIGURE 6
AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE GRADIENT
(ICAO)



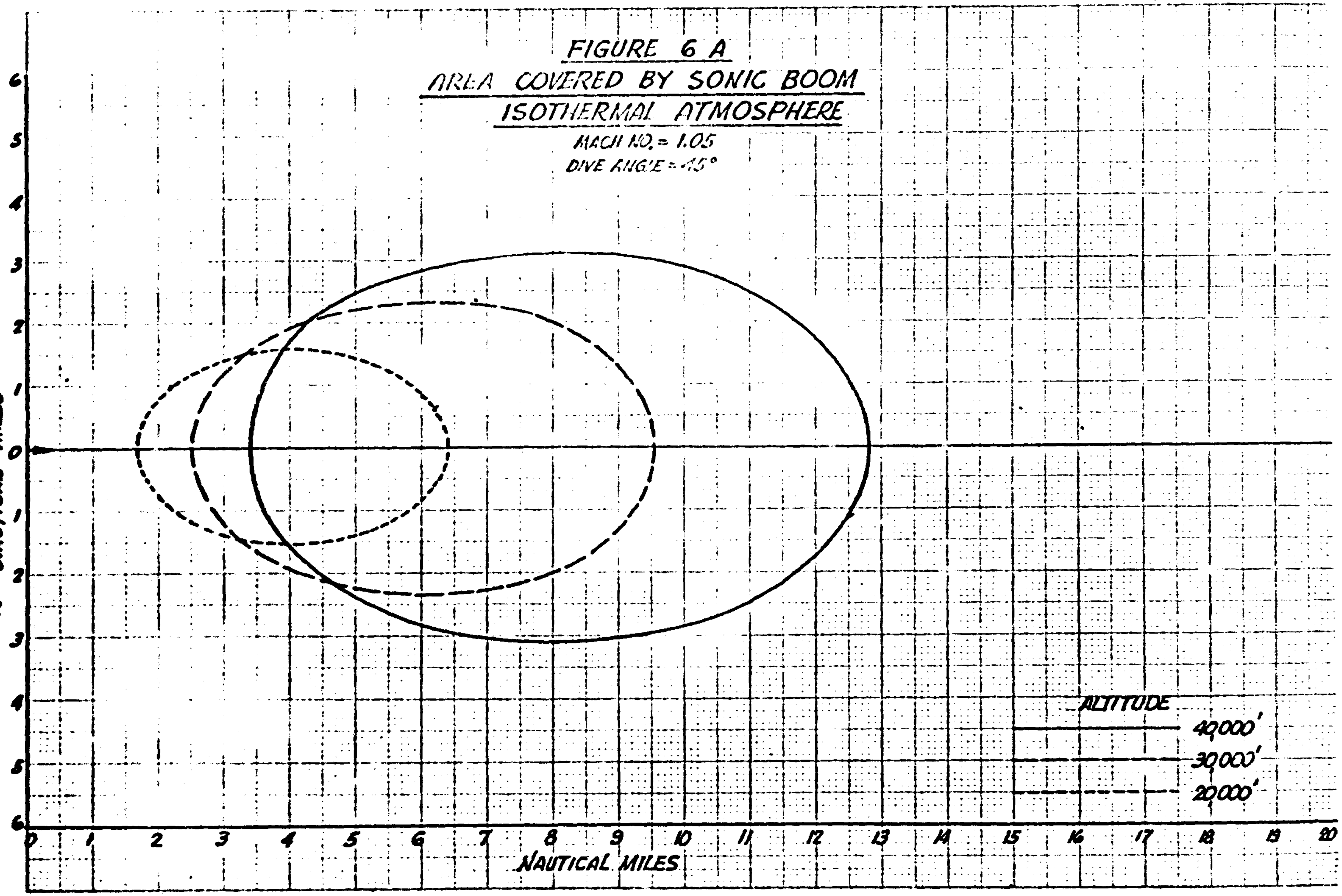


FIGURE 6 A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 1.05
DIVE ANGLE = 45°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

FIGURE 7

AREA COVERED BY SONIC BOOM

STANDARD TEMPERATURE GRADIENT

(ICAO)

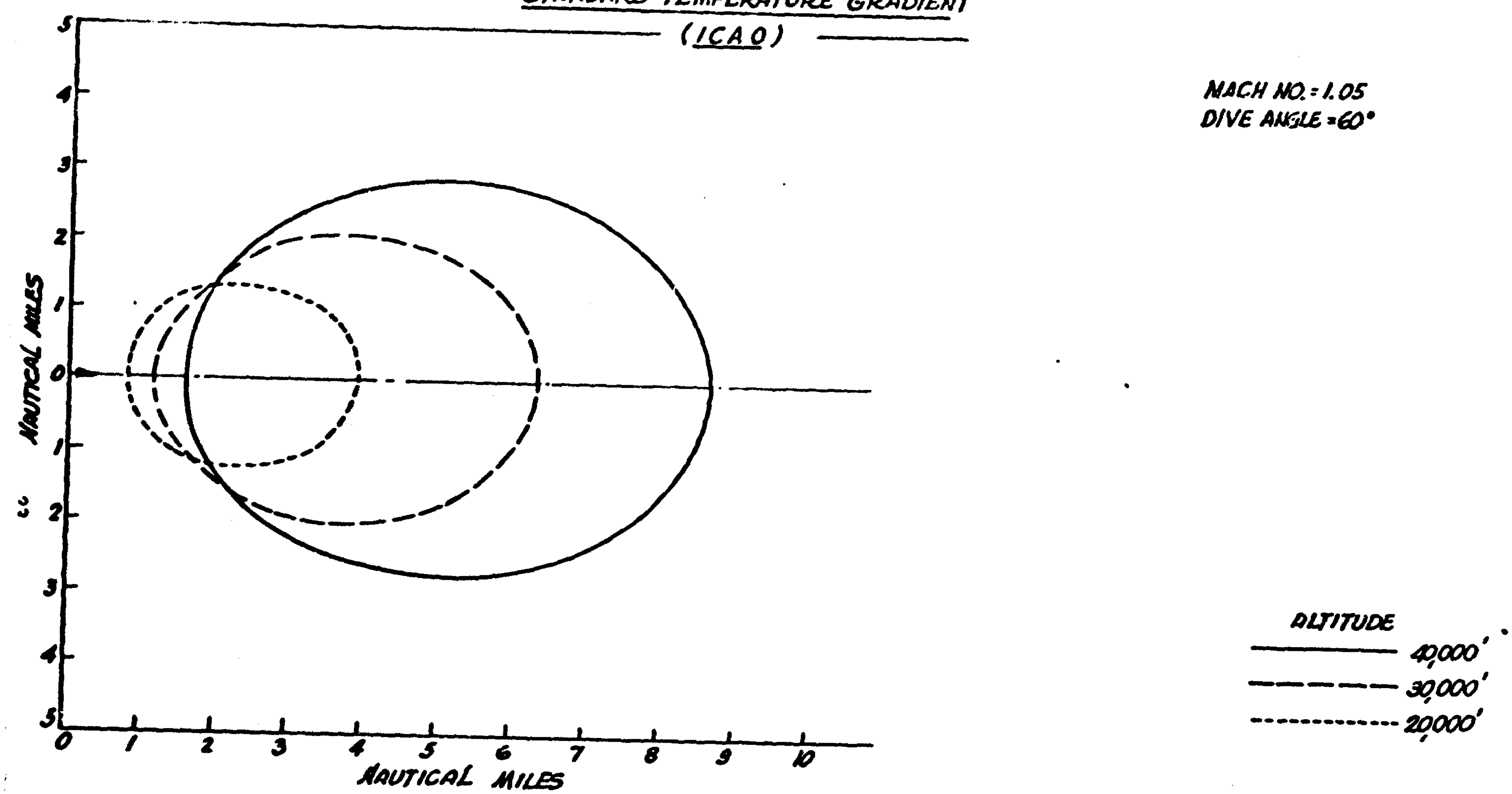


FIGURE 7 A

AREA COVERED BY SONIC BOOM

ISOTHERMAL ATMOSPHERE

MACH NO. = 1.05

DIVE ANGLE = 60°

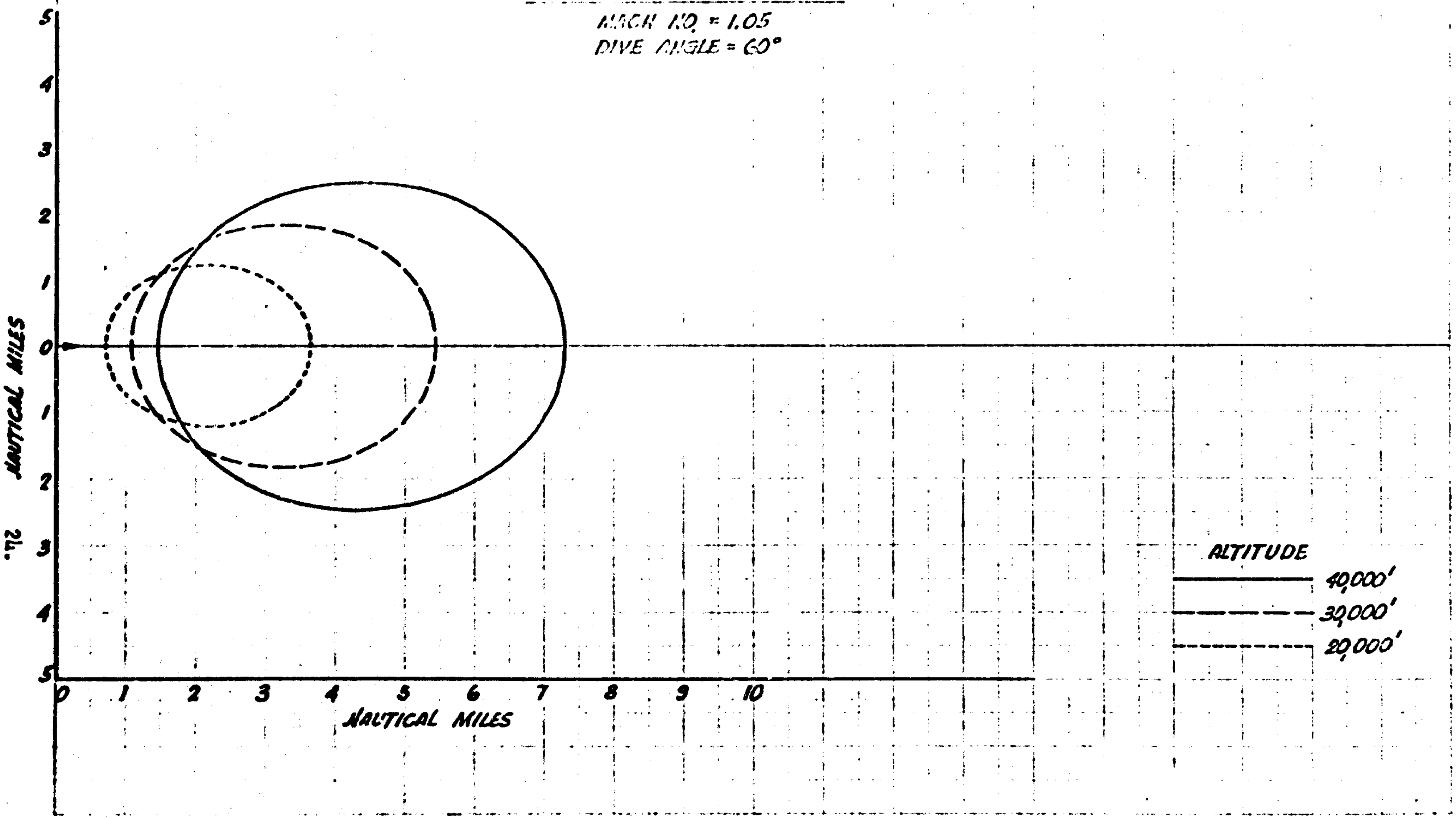


FIG. 8

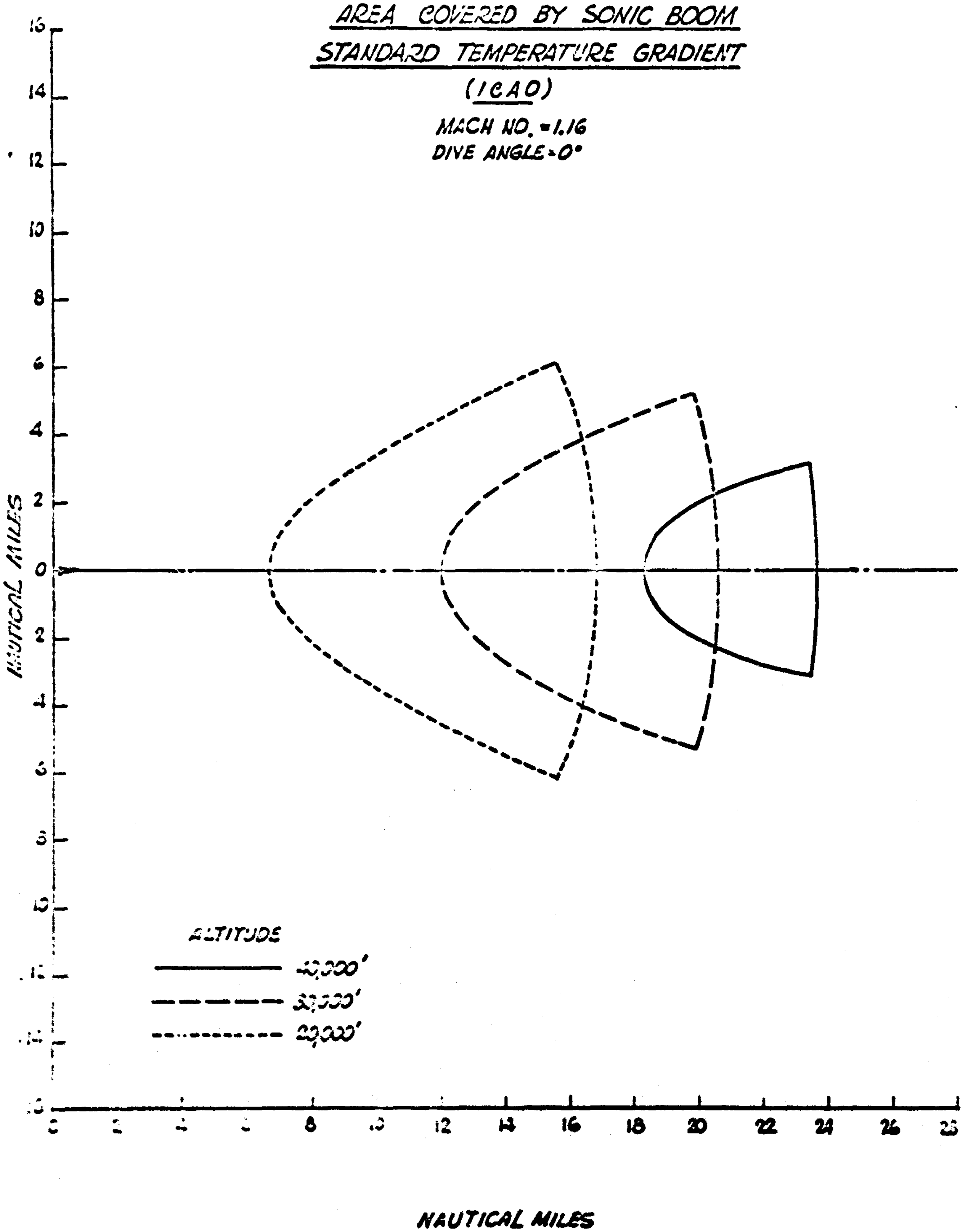
AREA COVERED BY SONIC BOOM

STANDARD TEMPERATURE GRADIENT

(ICAO)

MACH NO. = 1.16

DIVE ANGLE = 0°



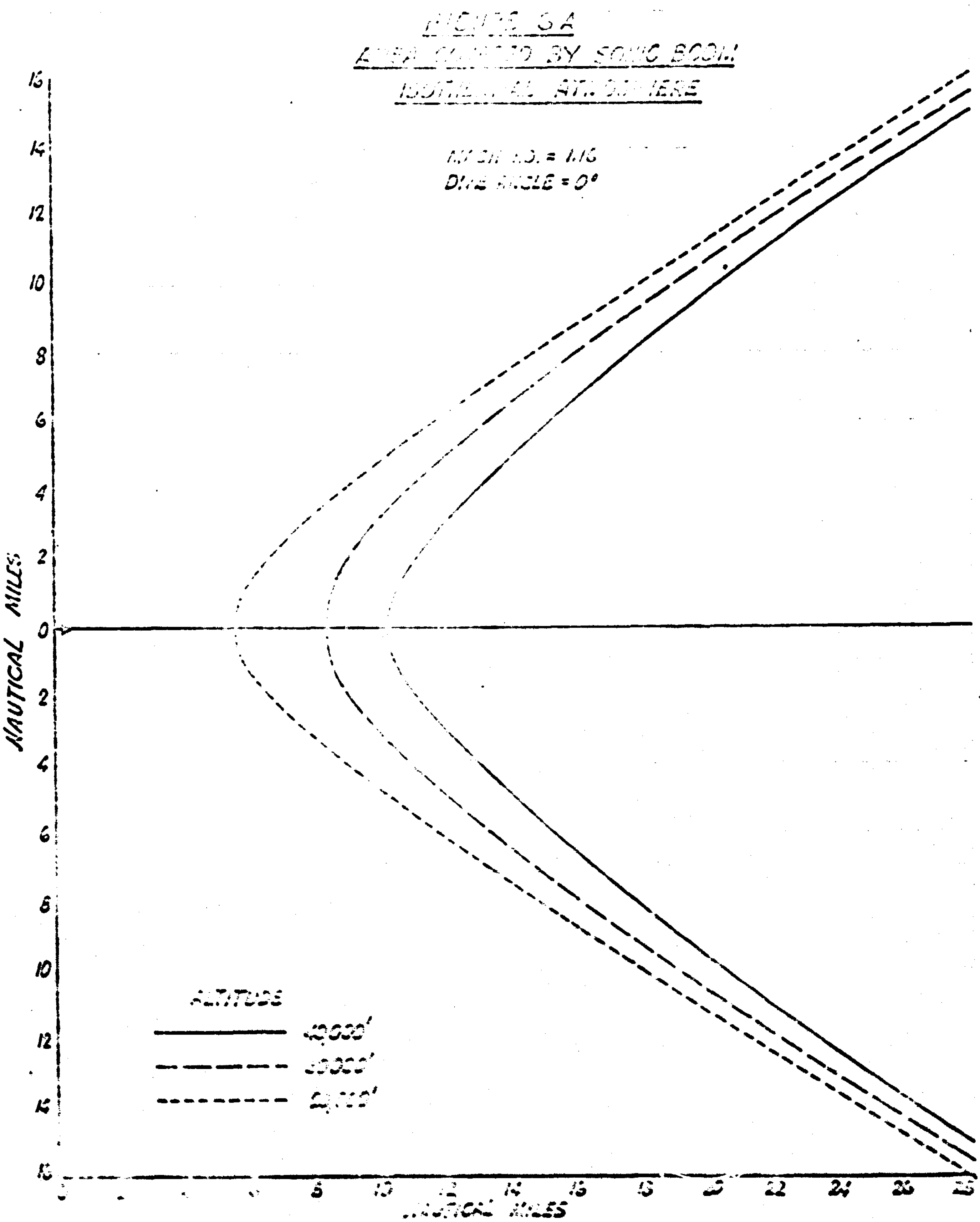
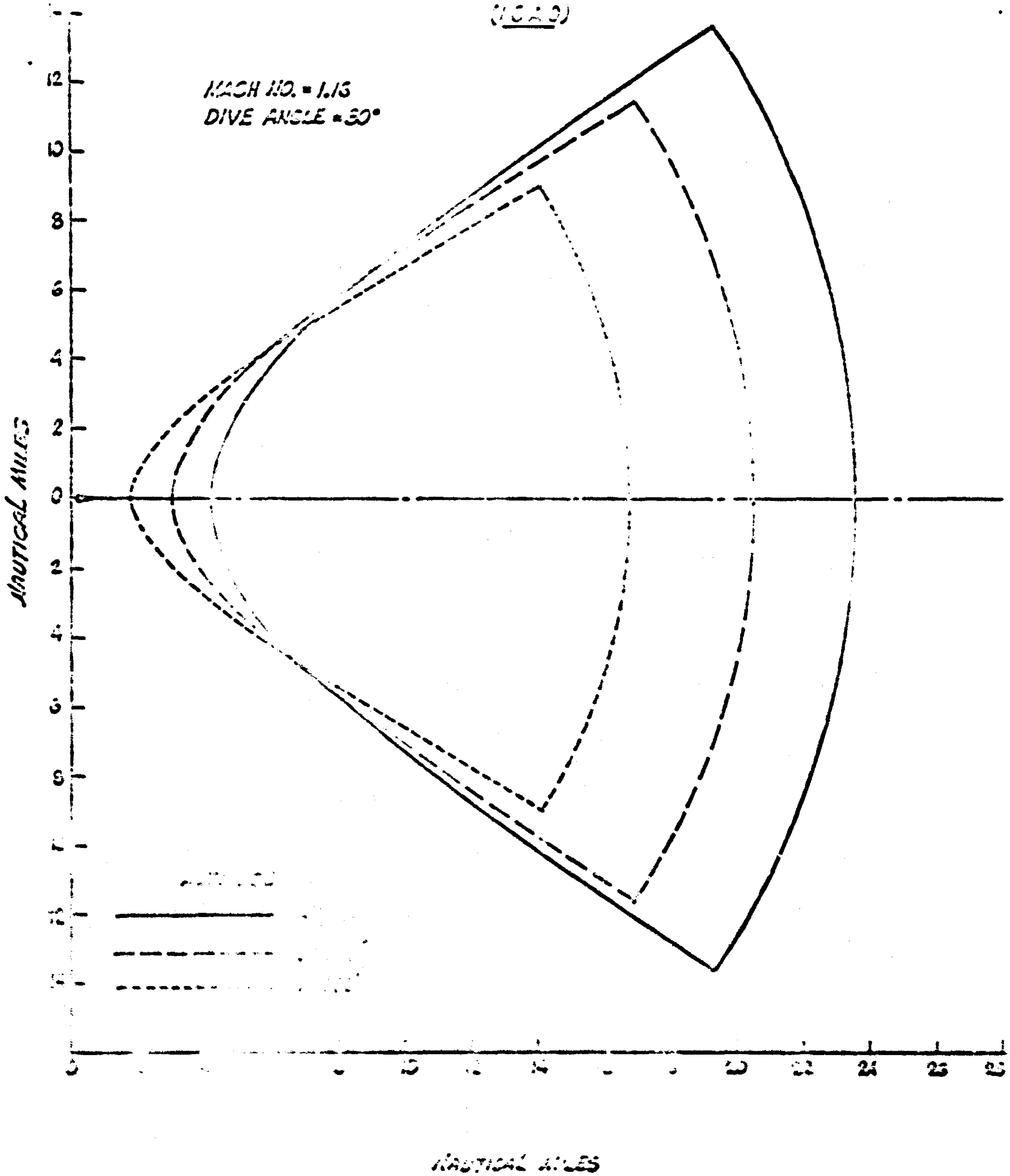

DIVE ANGLE = 0°
NAUTICAL MILES
0
2
4
6
8
10
12
14
16
ALTITUDE
NAUTICAL MILES
8
10
14
16
18
20
22
24
26
28

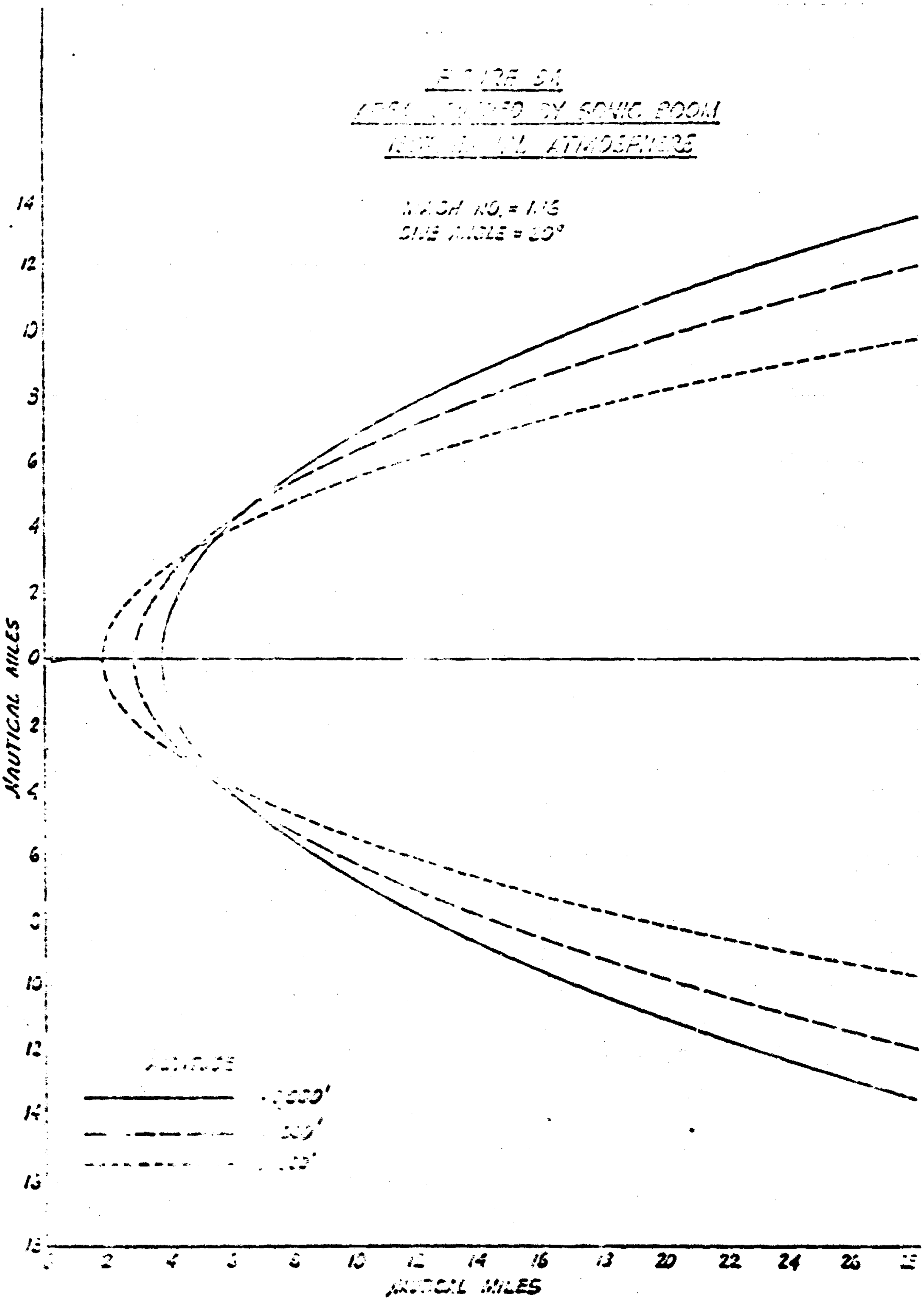
FIG. 9

AREA COVERED BY SONIC BOOM

STANDARD TEMPERATURE GRADIENT

(ICAO)




SONIC BOOM
ATMOSPHERE
14
12
10
6
4
2
0
2
6
10
12
NAUTICAL MILES
2
4
10
12
14
16
20
22
24
26
NAUTICAL MILES

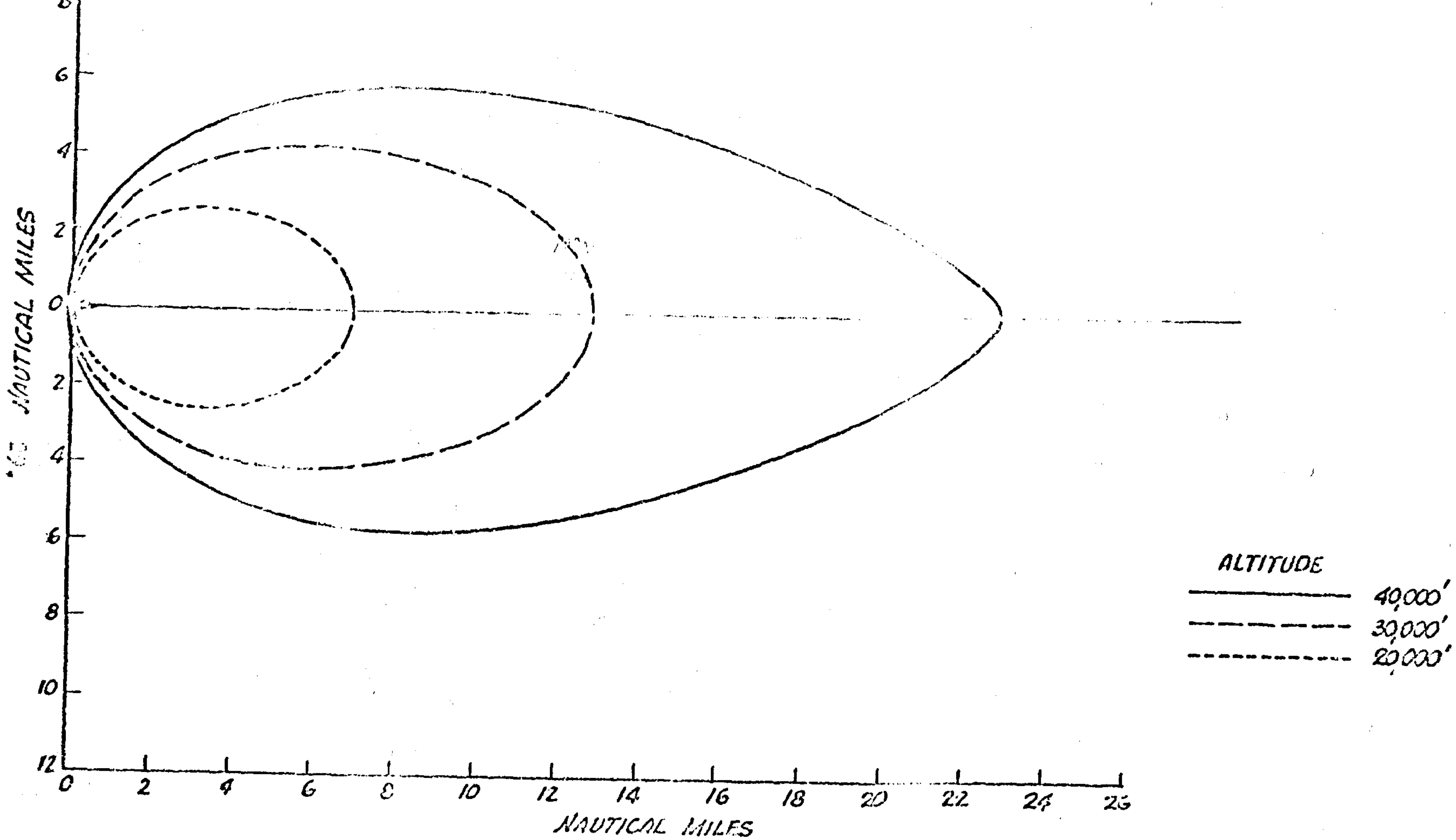
<u>FIGURE 10</u>

<u>AREA COVERED BY SONIC BOOM</u>

<u>STANDARD TEMPERATURE GRADIENT</u>

(ICAO)

MACH NO. = 1.15 DIVE ANGLE = 45°



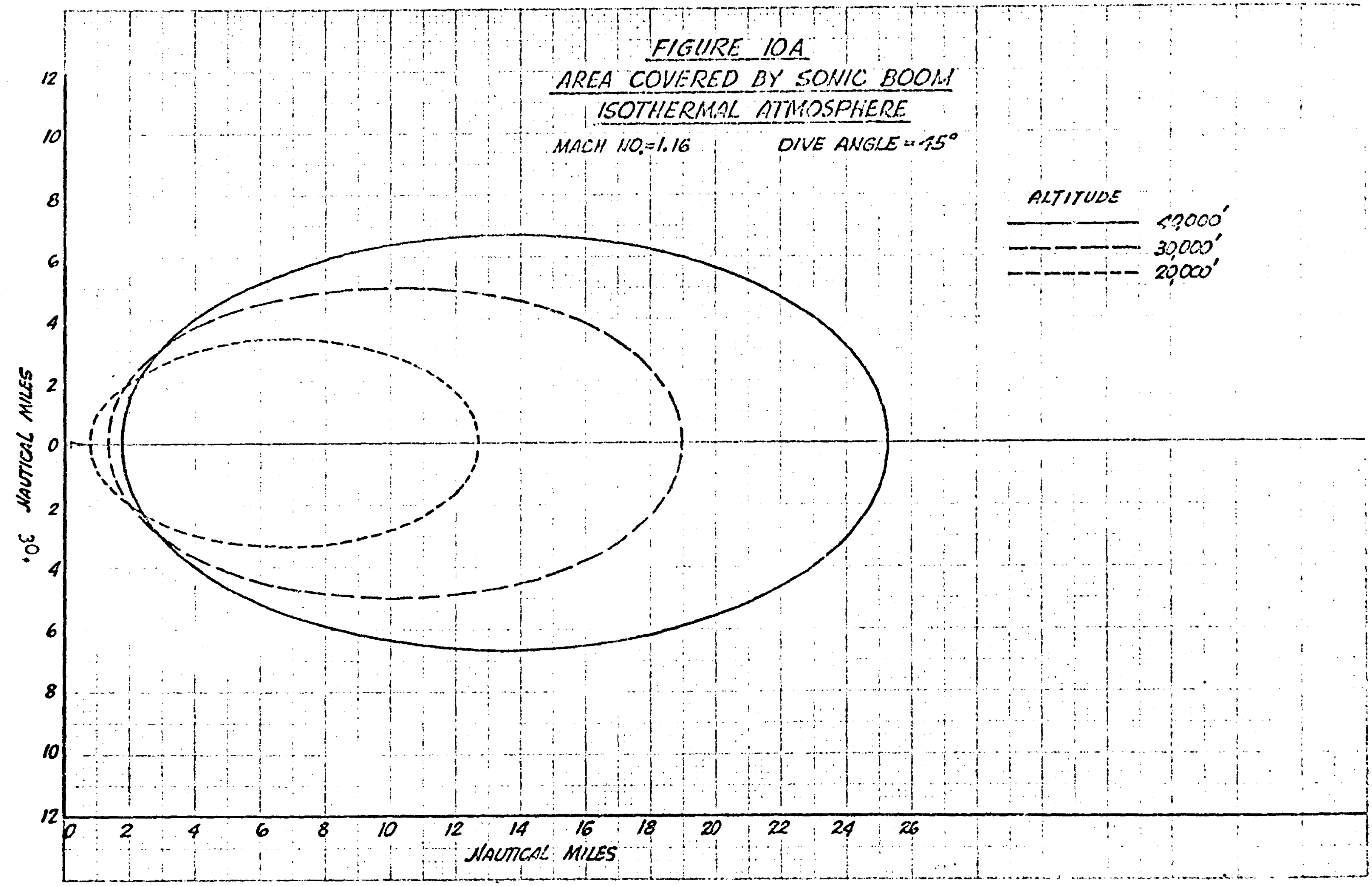


FIGURE 10A

AREA COVERED BY SONIC BOOM

ISOTHERMAL ATMOSPHERE

MACH NO.=1.16 DIVE ANGLE = 45°

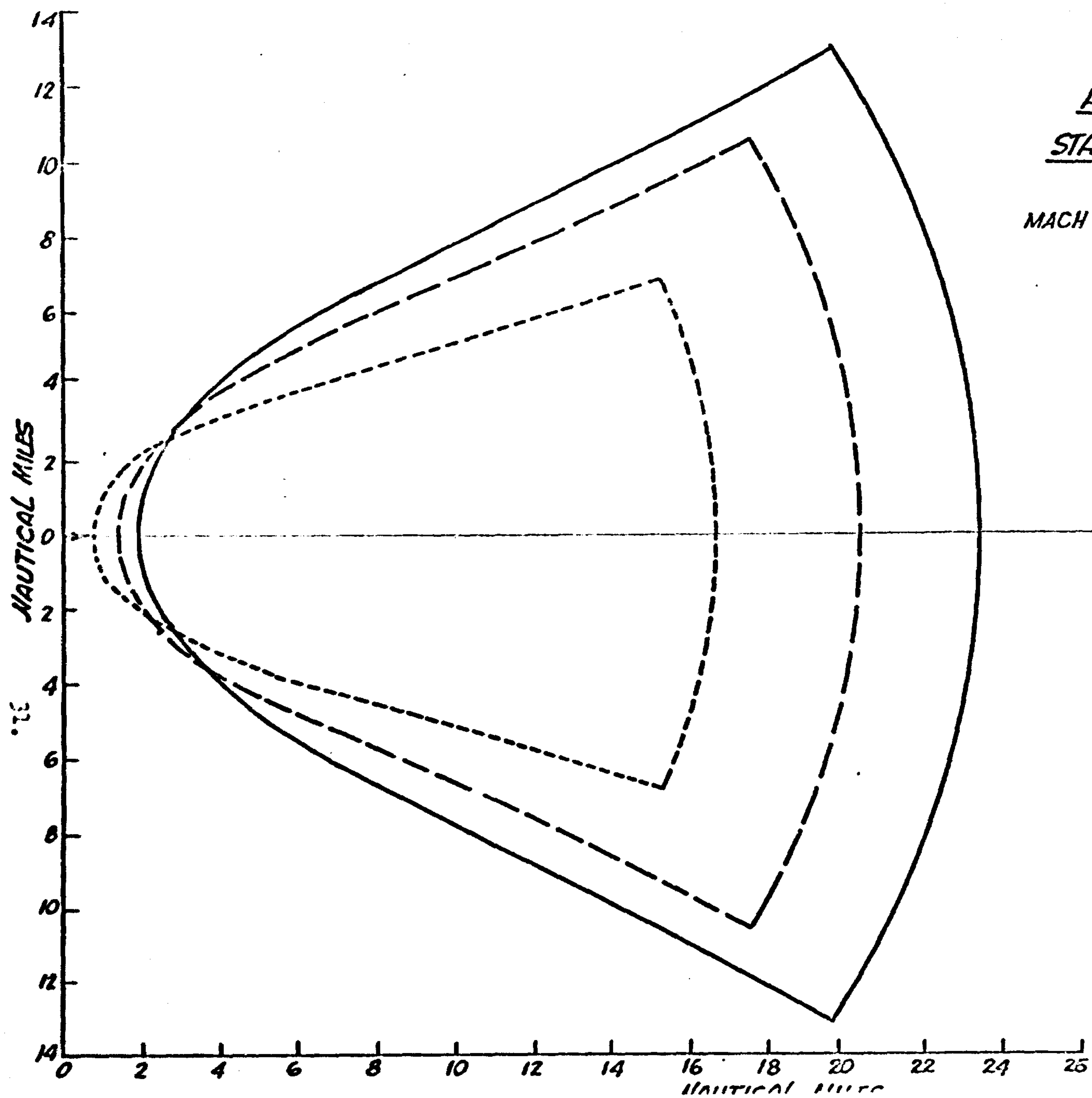
FIGURE II

AREA COVERED BY SONIC BOOM

STANDARD TEMPERATURE GRADIENT

(ICAO)

MACH NO. = 1.16 DIVE ANGLE = 60°



ALTITUDE

———— 40,000'

— — — — 30,000'

- - - - - - 20,000'

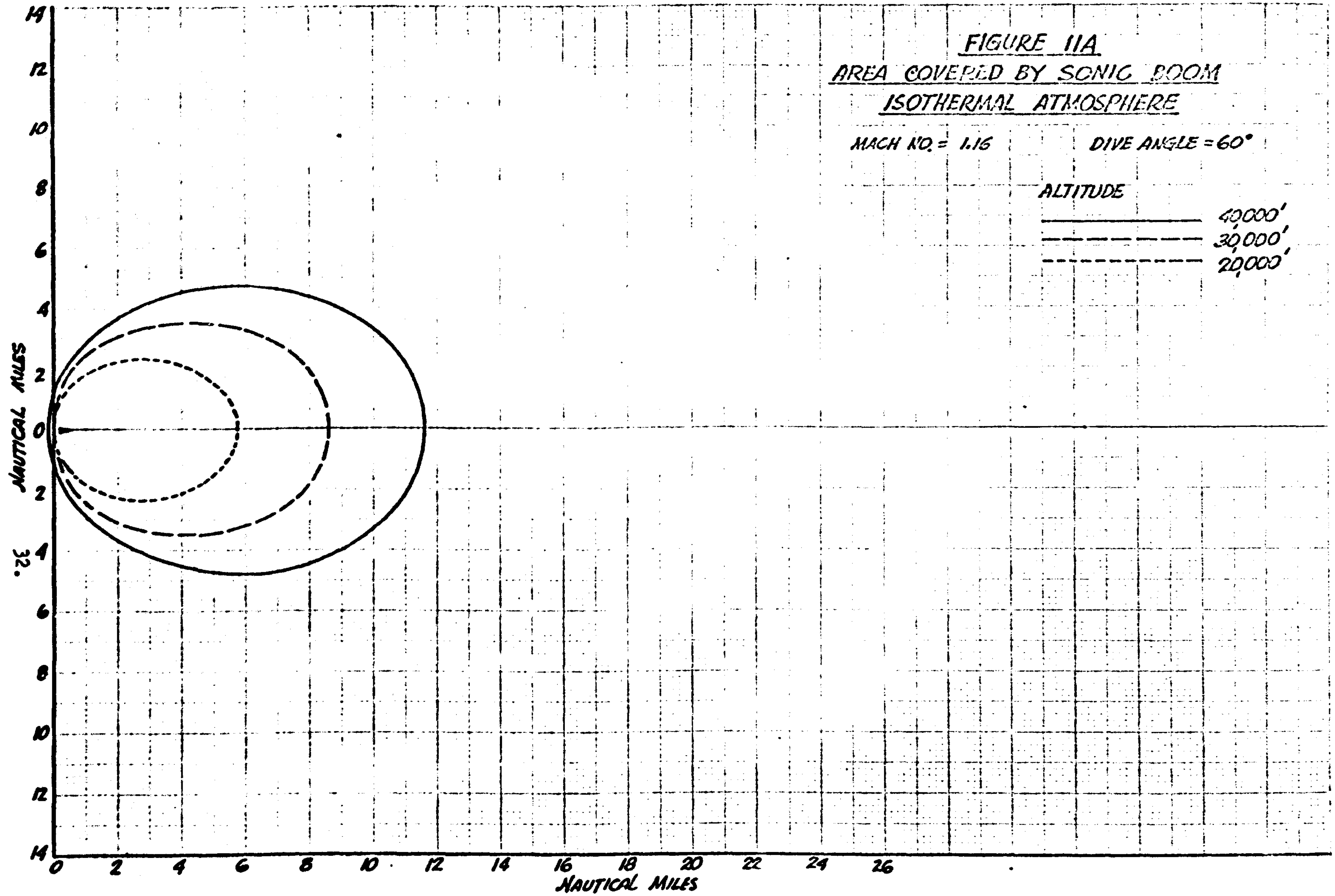


FIGURE 11A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE

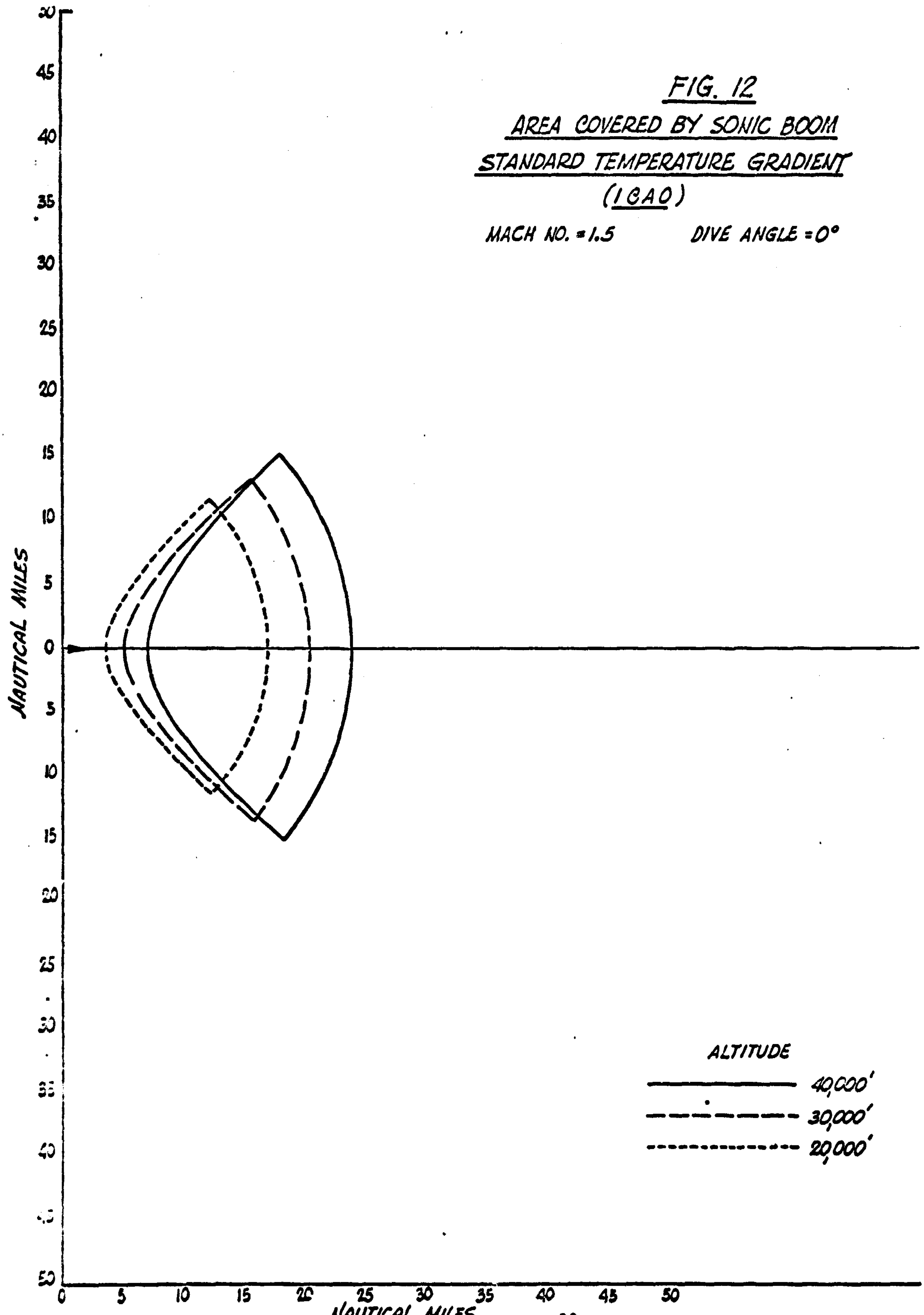
FIG. 12

AREA COVERED BY SONIC BOOM

STANDARD TEMPERATURE GRADIENT

(ICAO)

MACH NO. = 1.5 DIVE ANGLE = 0°



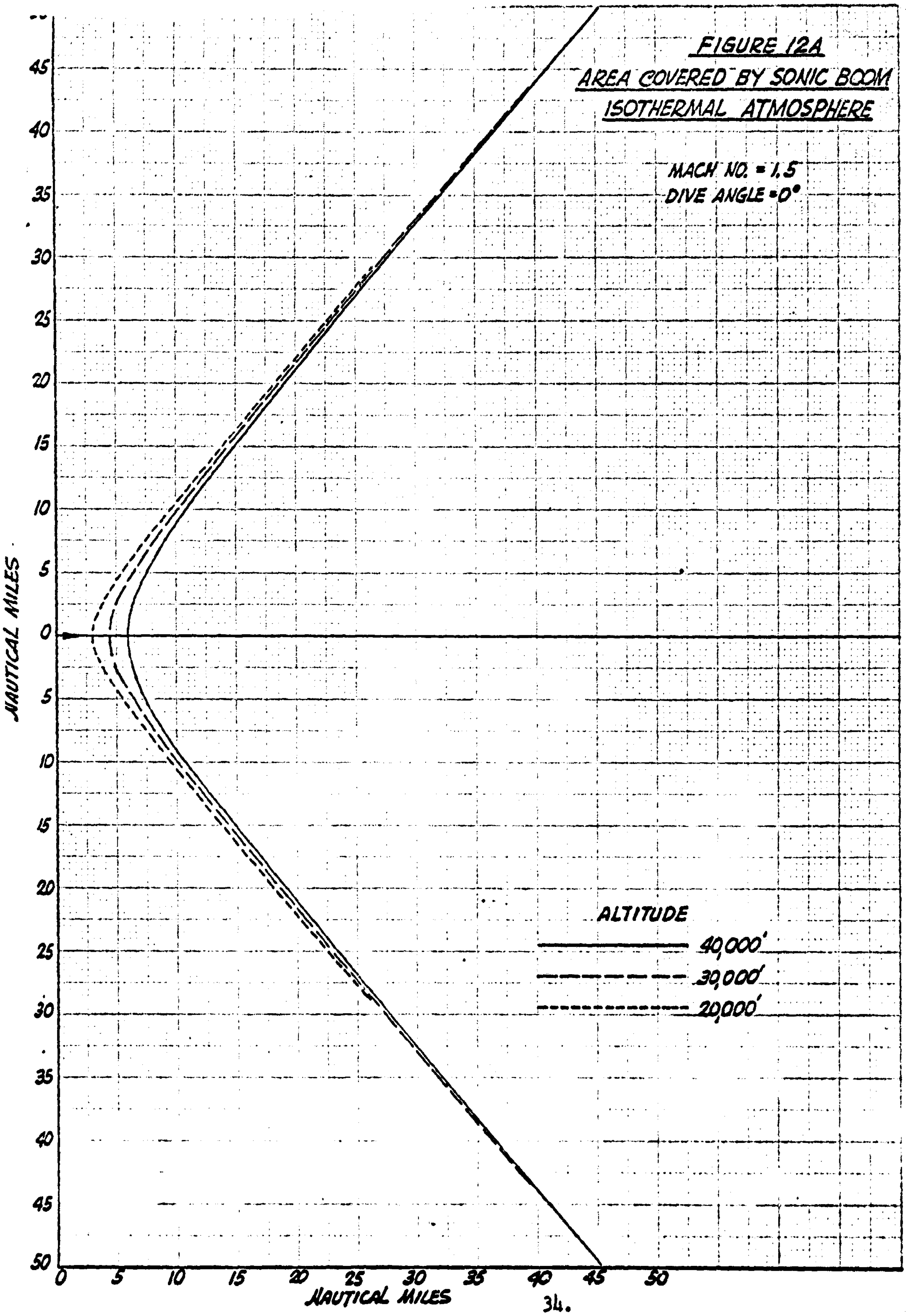


FIGURE 12A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 1.5
DIVE ANGLE = 0°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
0
5
10
15
20
25
30
35
40
45
50

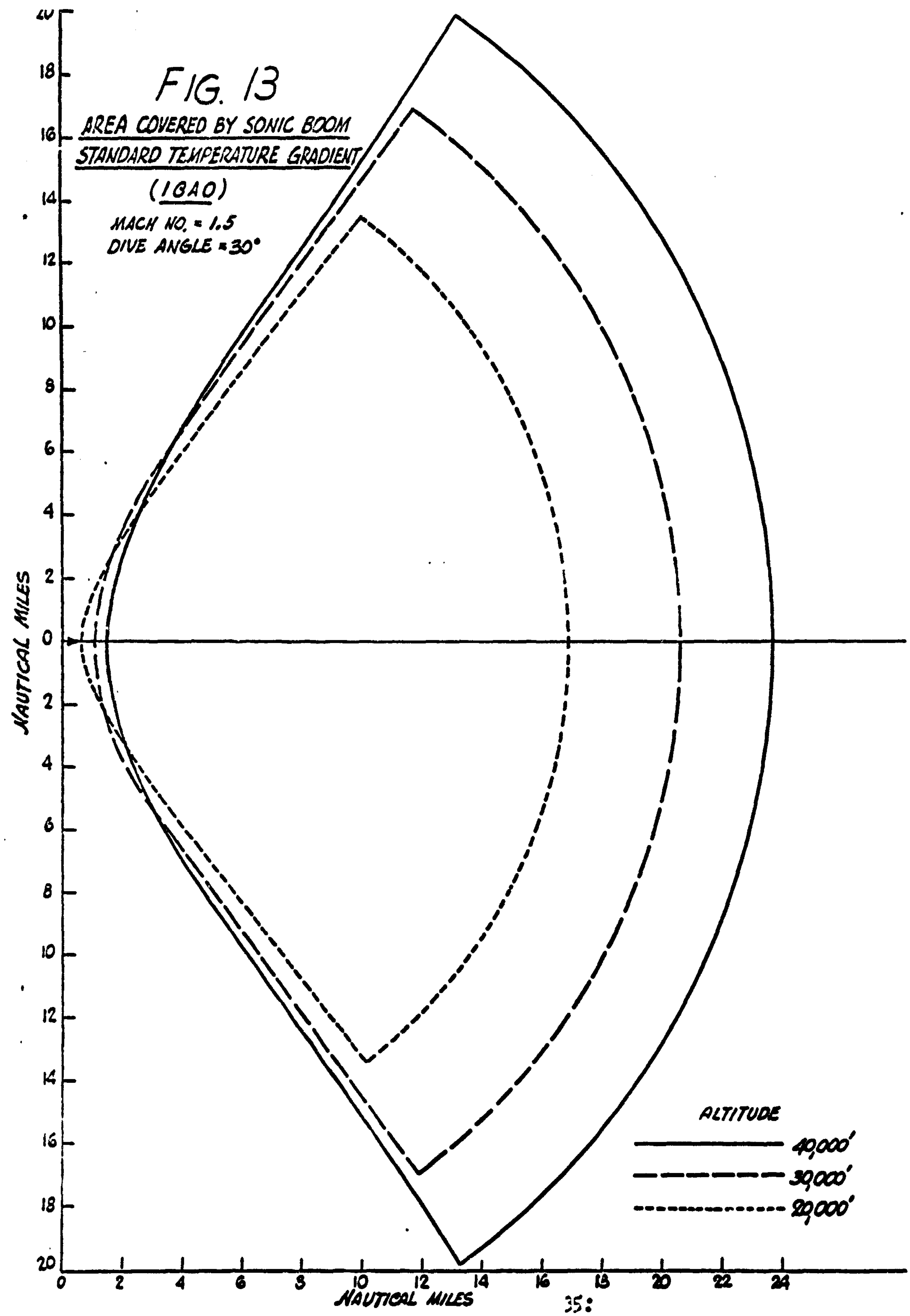


FIG. 13
AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE GRADIENT
(ICAO)
MACH NO. = 1.5
DIVE ANGLE = 30°
NAUTICAL MILES
NAUTICAL MILES
ALTITUDE
40,000'
30,000'
20,000'

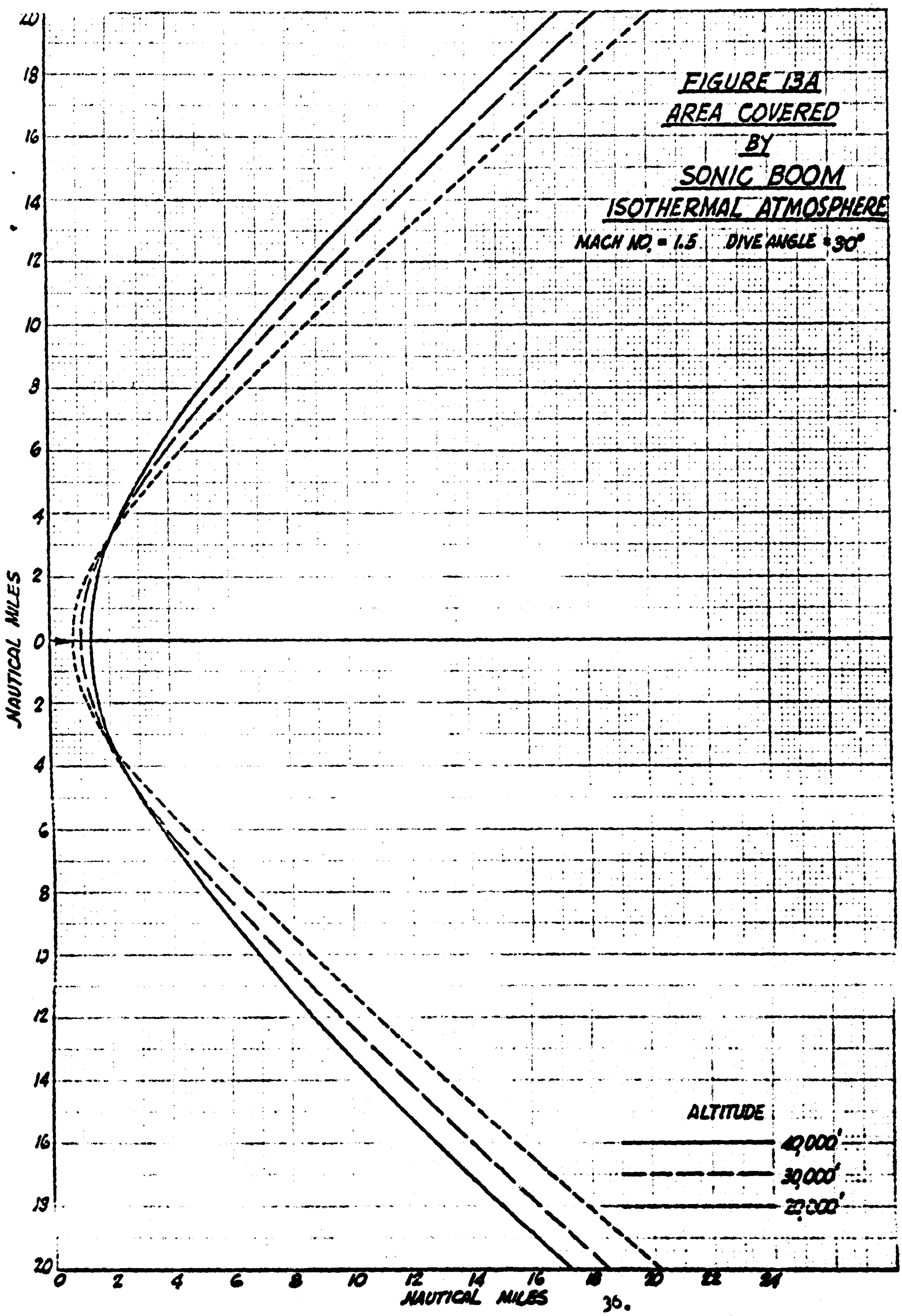


FIGURE 13A
AREA COVERED
BY
SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 1.5 DIVE ANGLE = 30°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
20
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
18
20
0
2
4
6
8
10
12
14
16
18
20
22
24

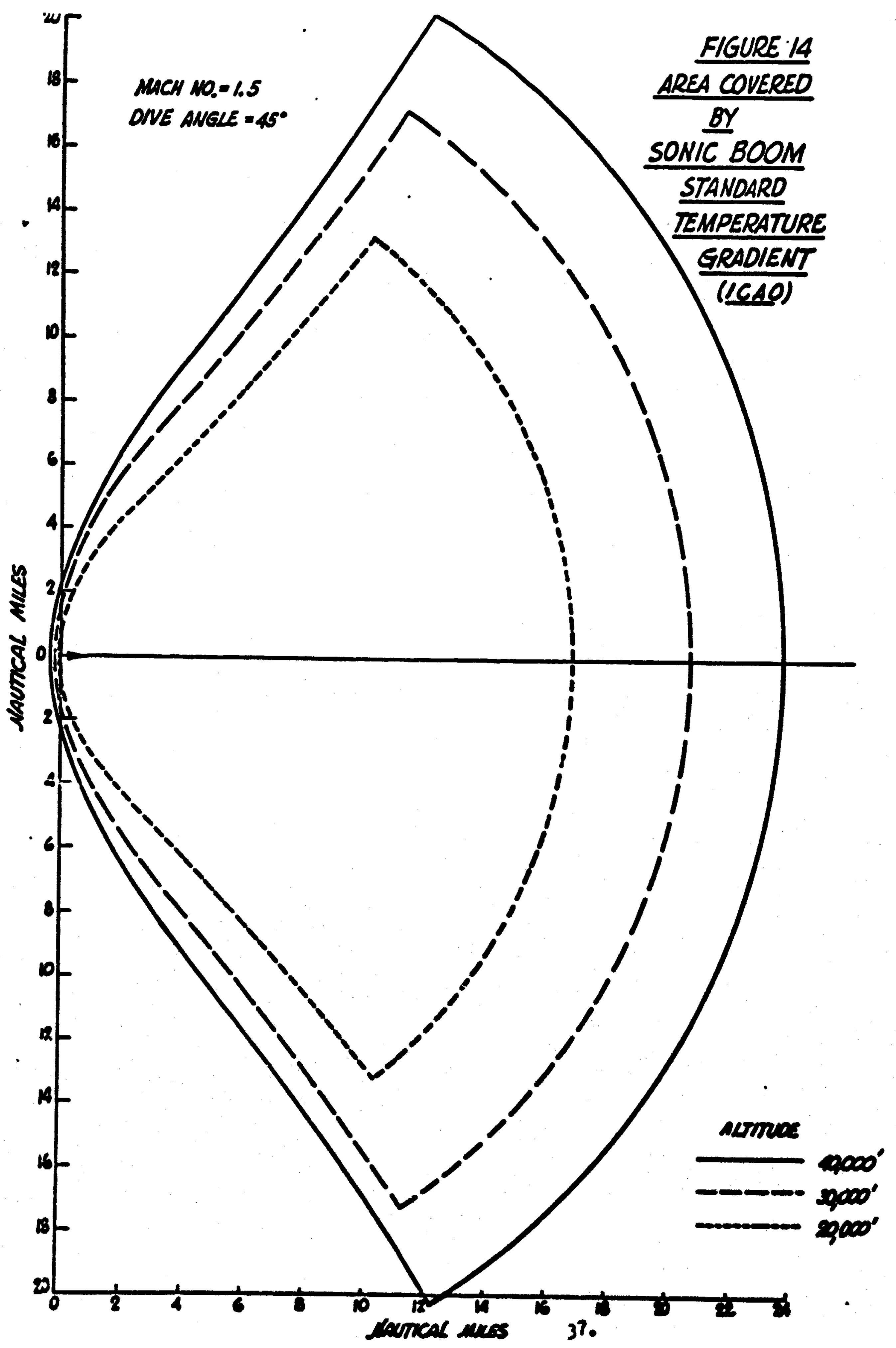


FIGURE 14
AREA COVERED
BY
SONIC BOOM
STANDARD
TEMPERATURE
GRADIENT
(ICAO)
MACH NO.= 1.5
DIVE ANGLE = 45°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
0
2
4
6
8
10
12
14
16
18
20
22
24

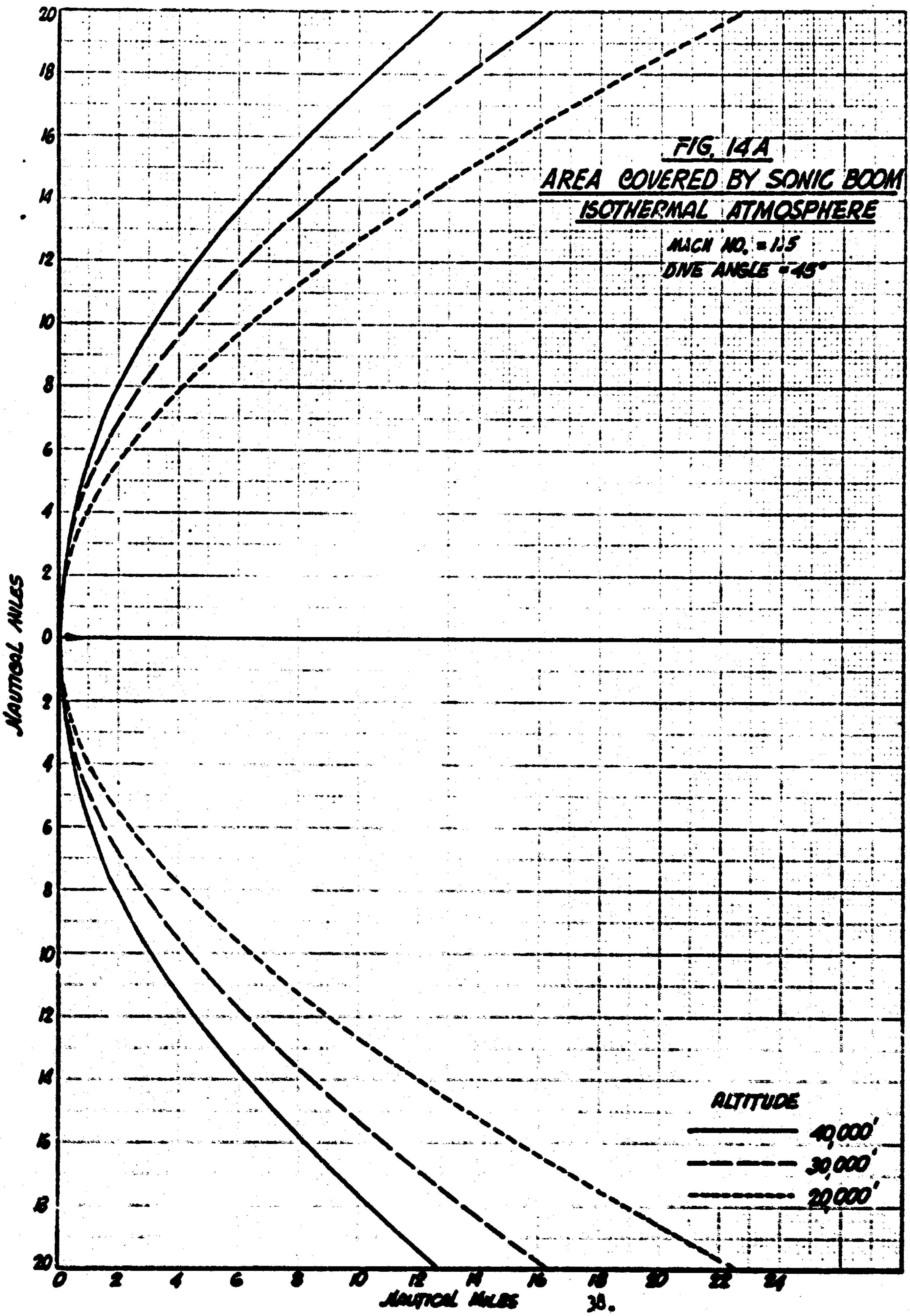
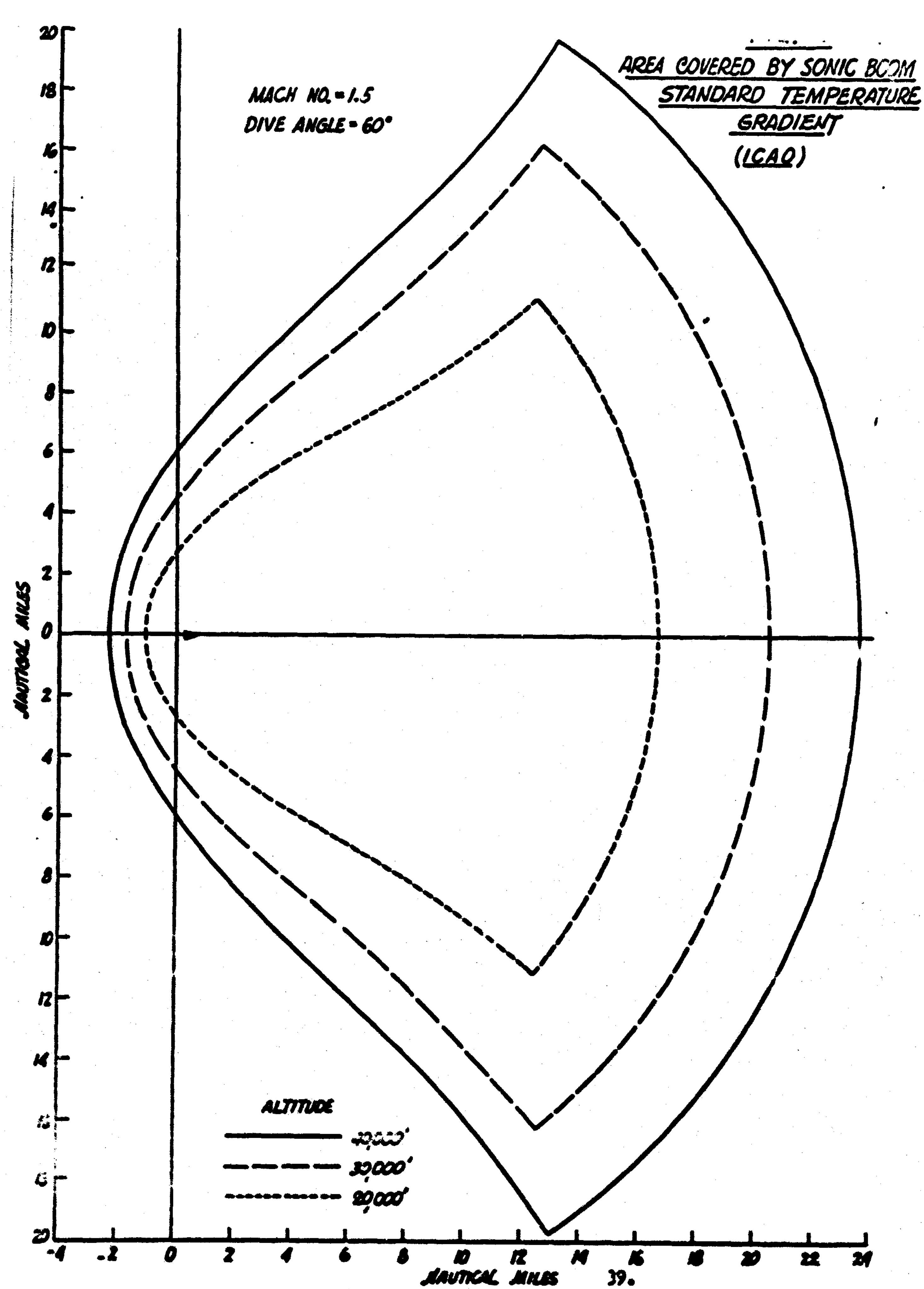


FIG. 14A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 1.5
DIVE ANGLE = 45°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
20
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
18
20
0
2
4
6
8
10
12
14
16
18
20
22
24
NAUTICAL MILES



AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE GRADIENT
(ICAO)
MACH NO. = 1.5
DIVE ANGLE = 60°
ALTITUDE
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES

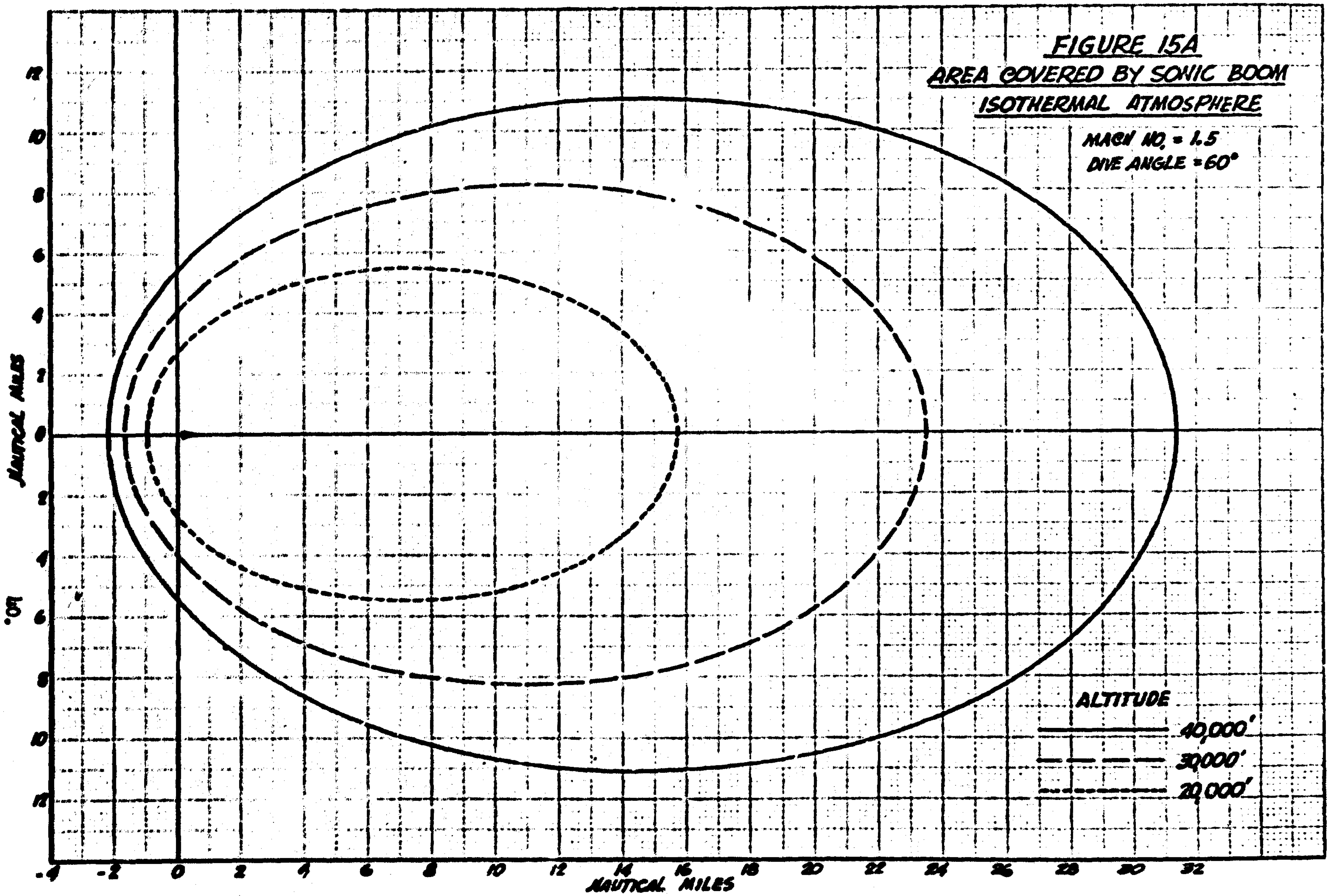


FIGURE 15A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 1.5
DIVE ANGLE = 60°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
-4
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
12
10
8
6
4
2
0
2
4
6
8
10
12

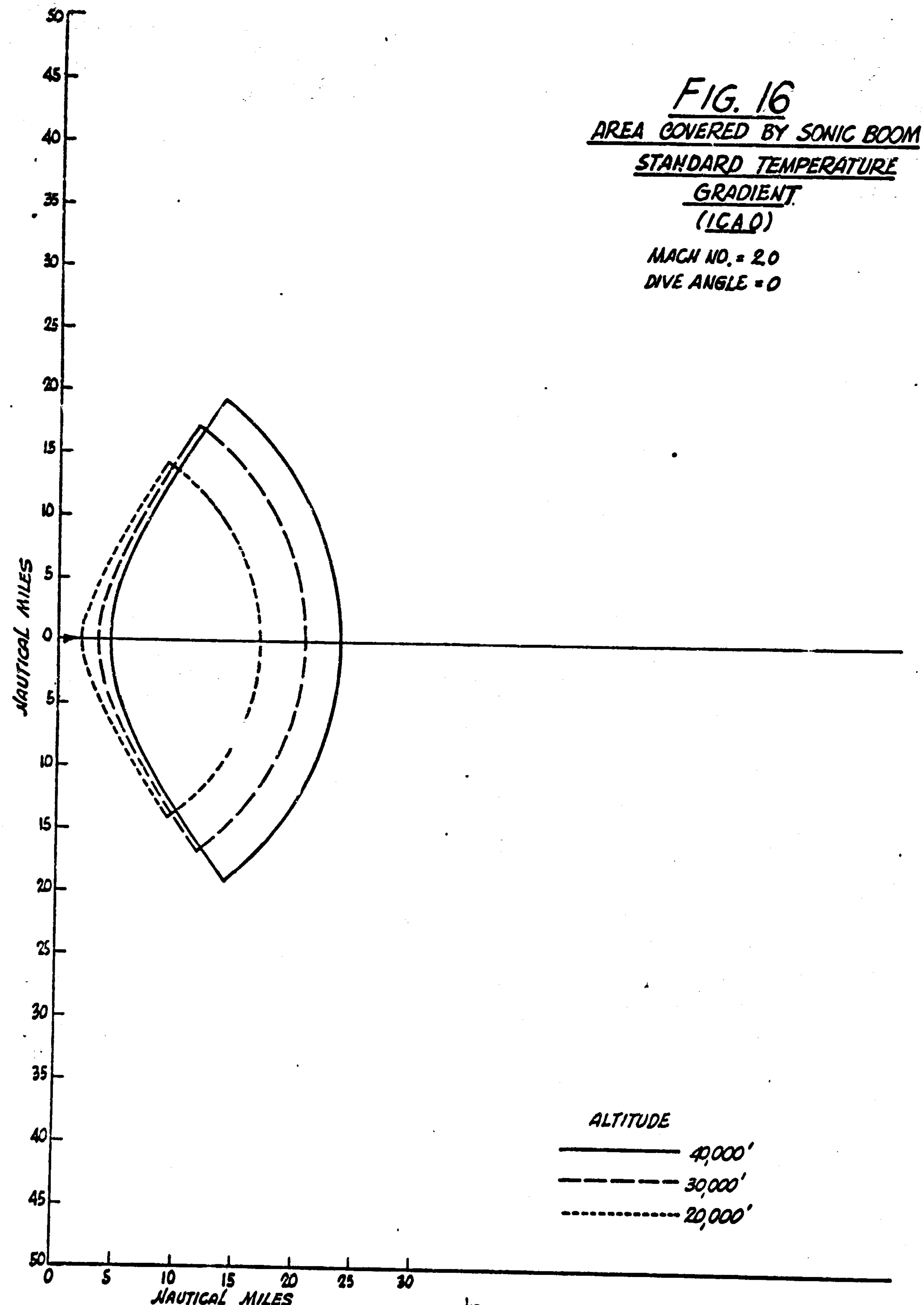


FIG. 16
AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE
GRADIENT
(ICAO)
MACH NO. = 2.0
DIVE ANGLE = 0
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20
25
30

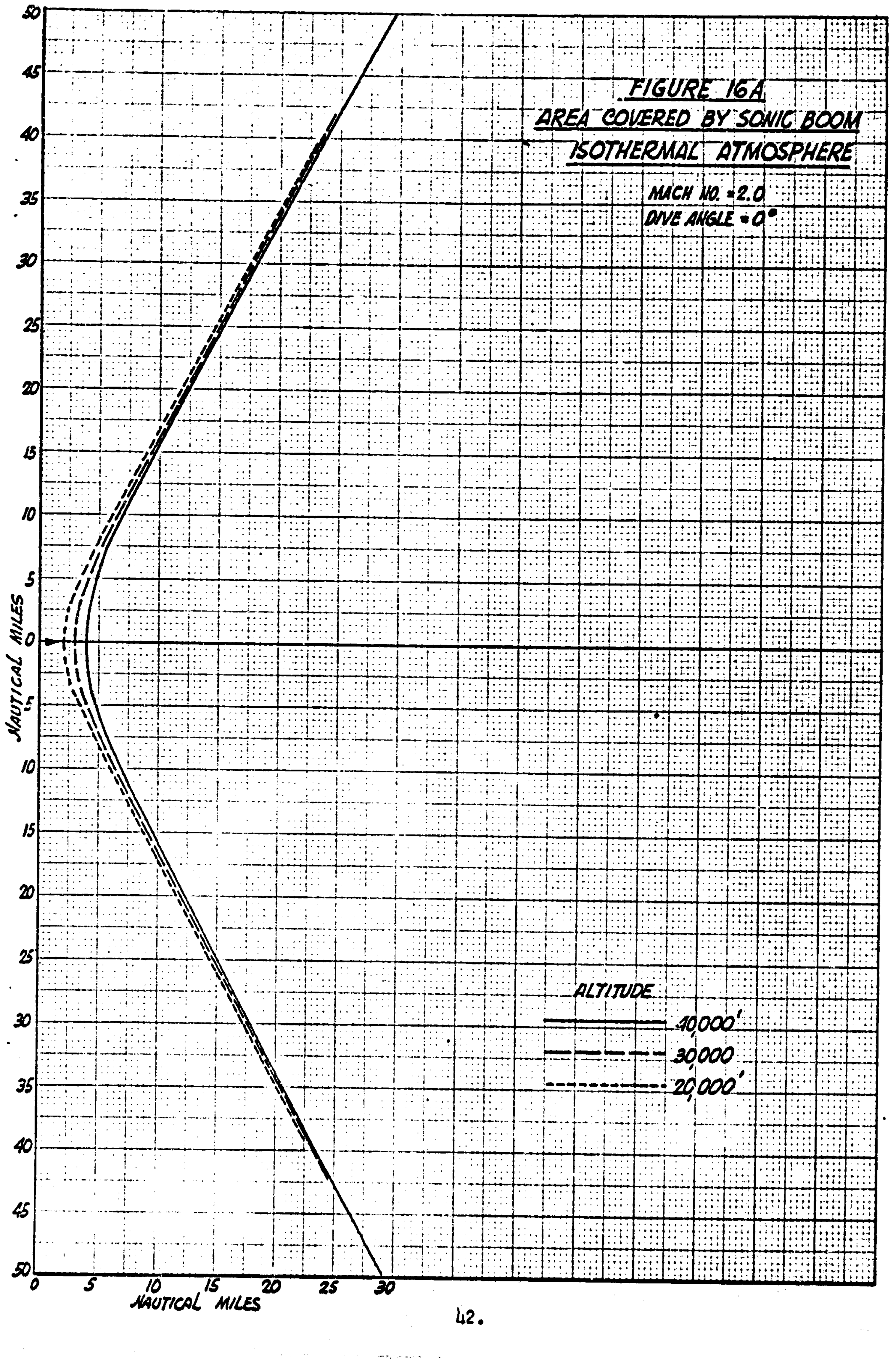
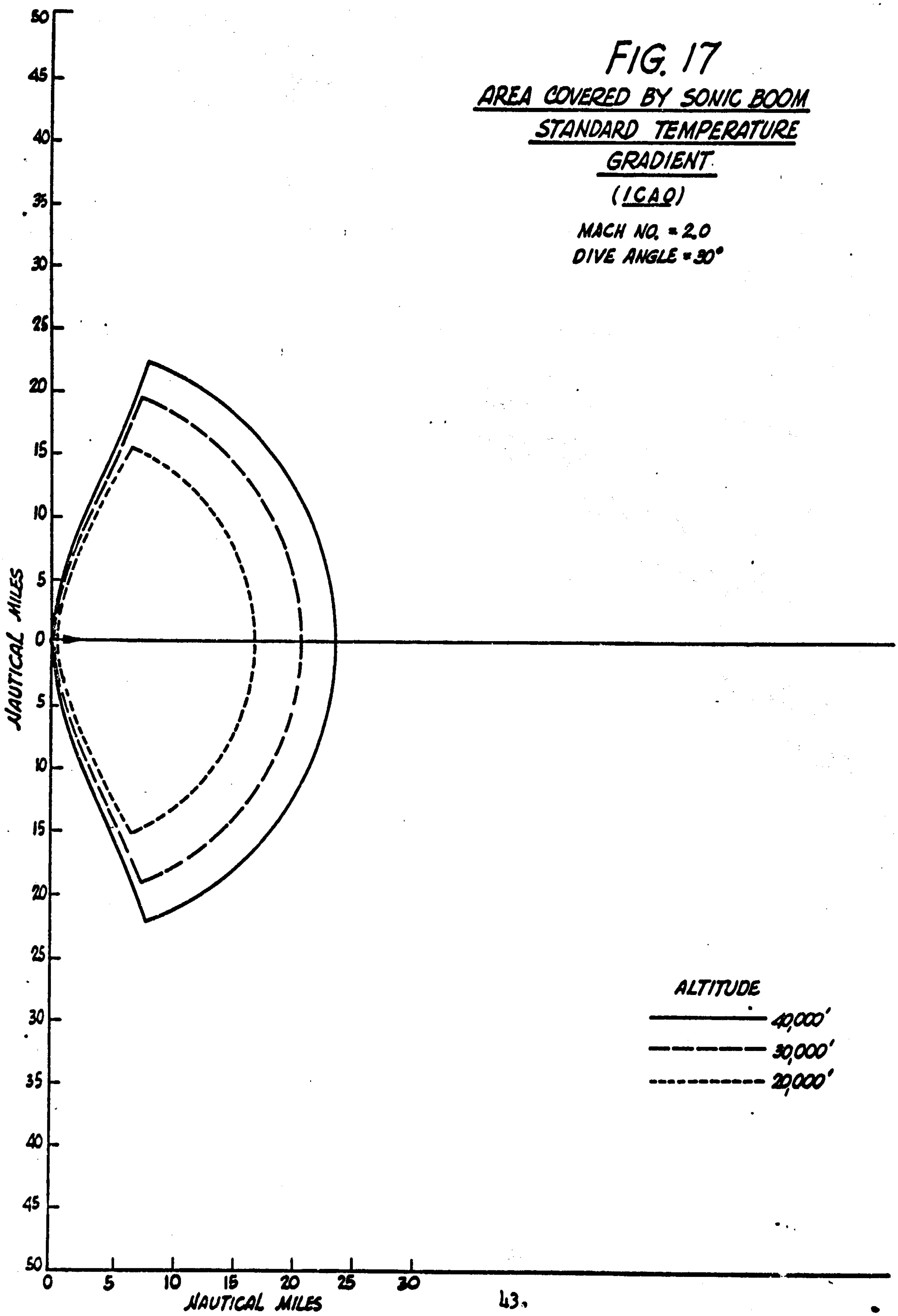


FIGURE 16A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 2.0
DIVE ANGLE = 0°
ALTITUDE
40,000'
30,000
20,000'
NAUTICAL MILES
NAUTICAL MILES

FIG. 17

AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE
GRADIENT
(ICAO)

MACH NO. = 2.0
DIVE ANGLE = 30°



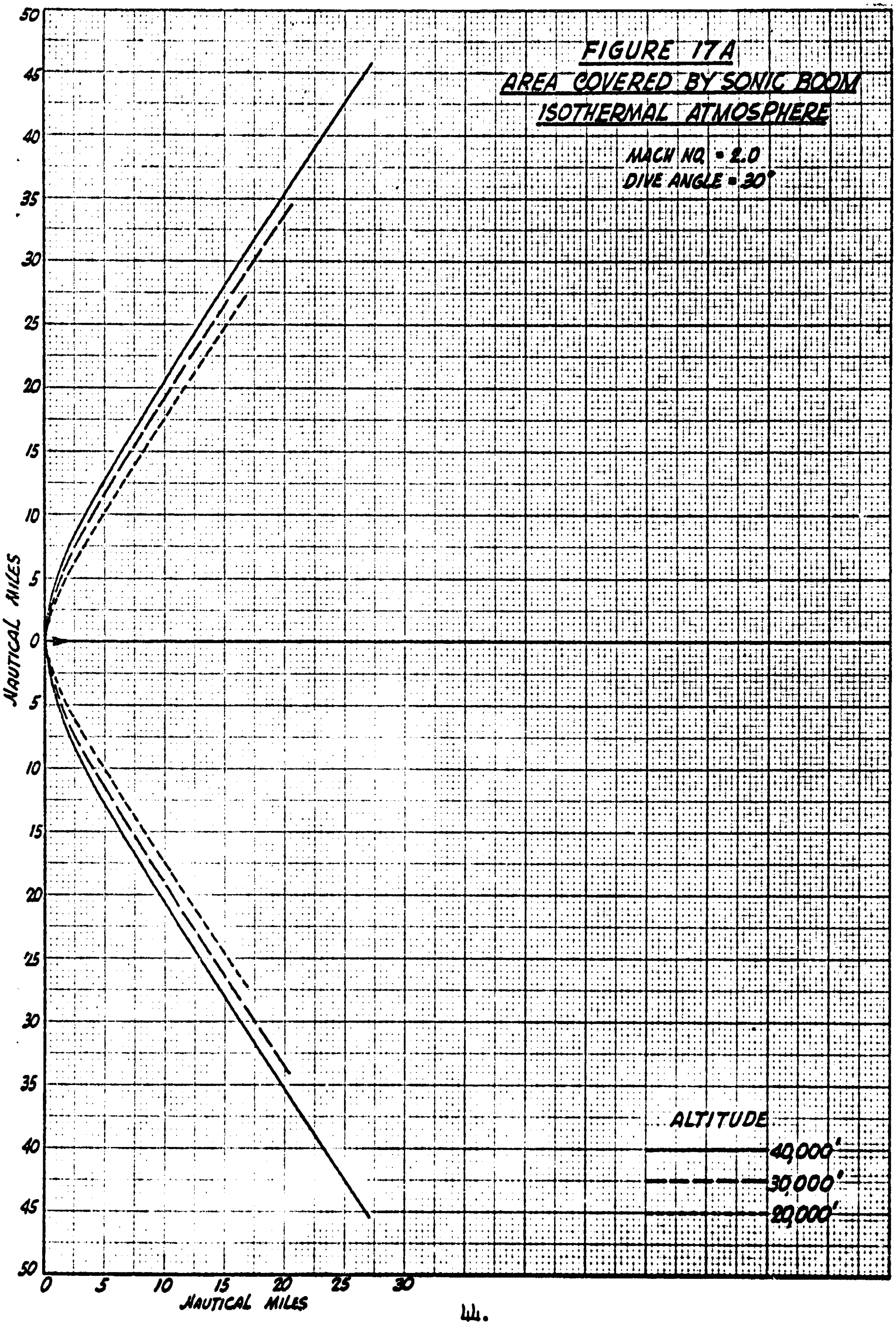


FIGURE 17A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 2.0
DIVE ANGLE = 30°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20
25
30

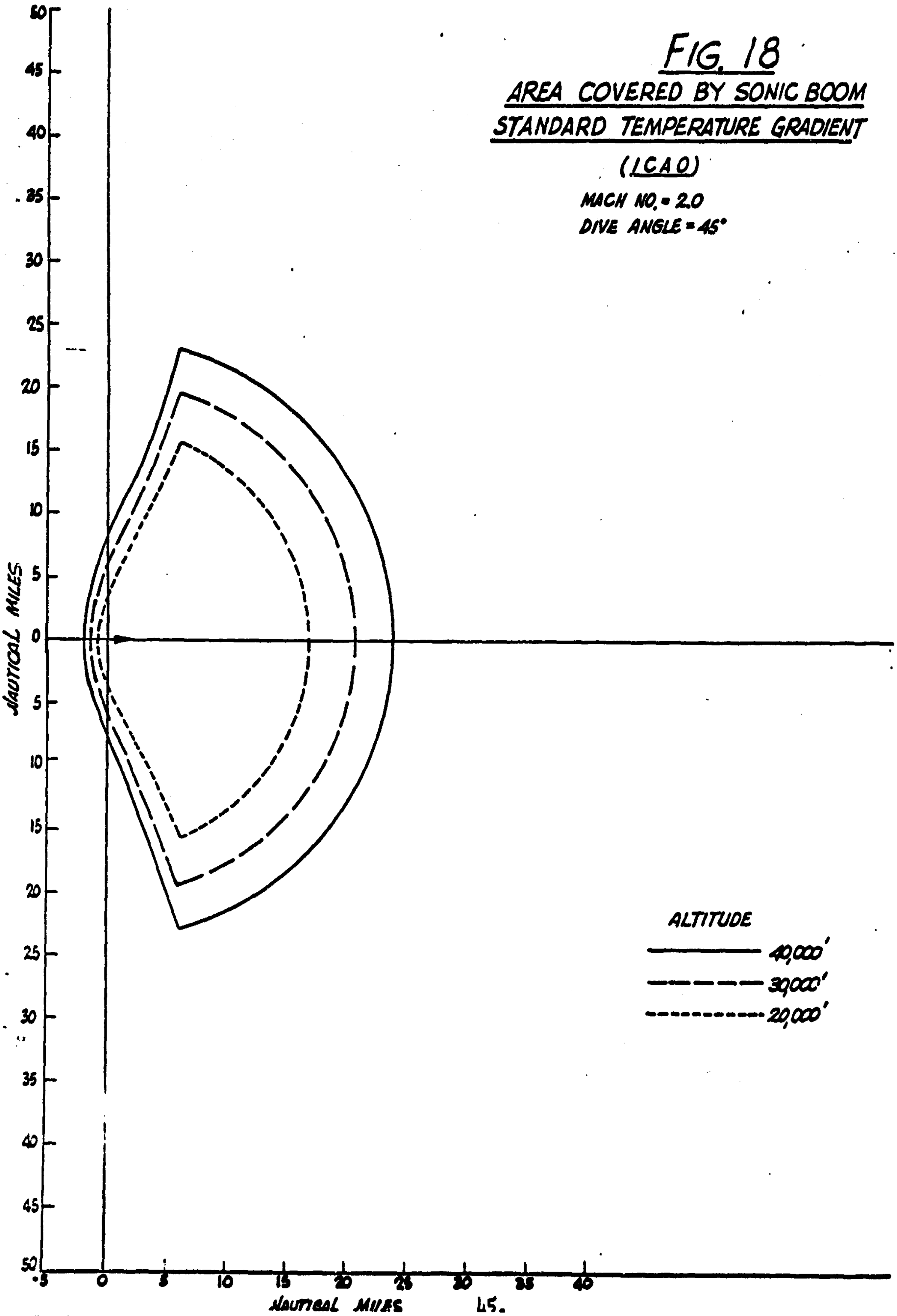


FIG. 18
AREA COVERED BY SONIC BOOM STANDARD TEMPERATURE GRADIENT (ICAO)

MACH NO. = 2.0
DIVE ANGLE = 45°

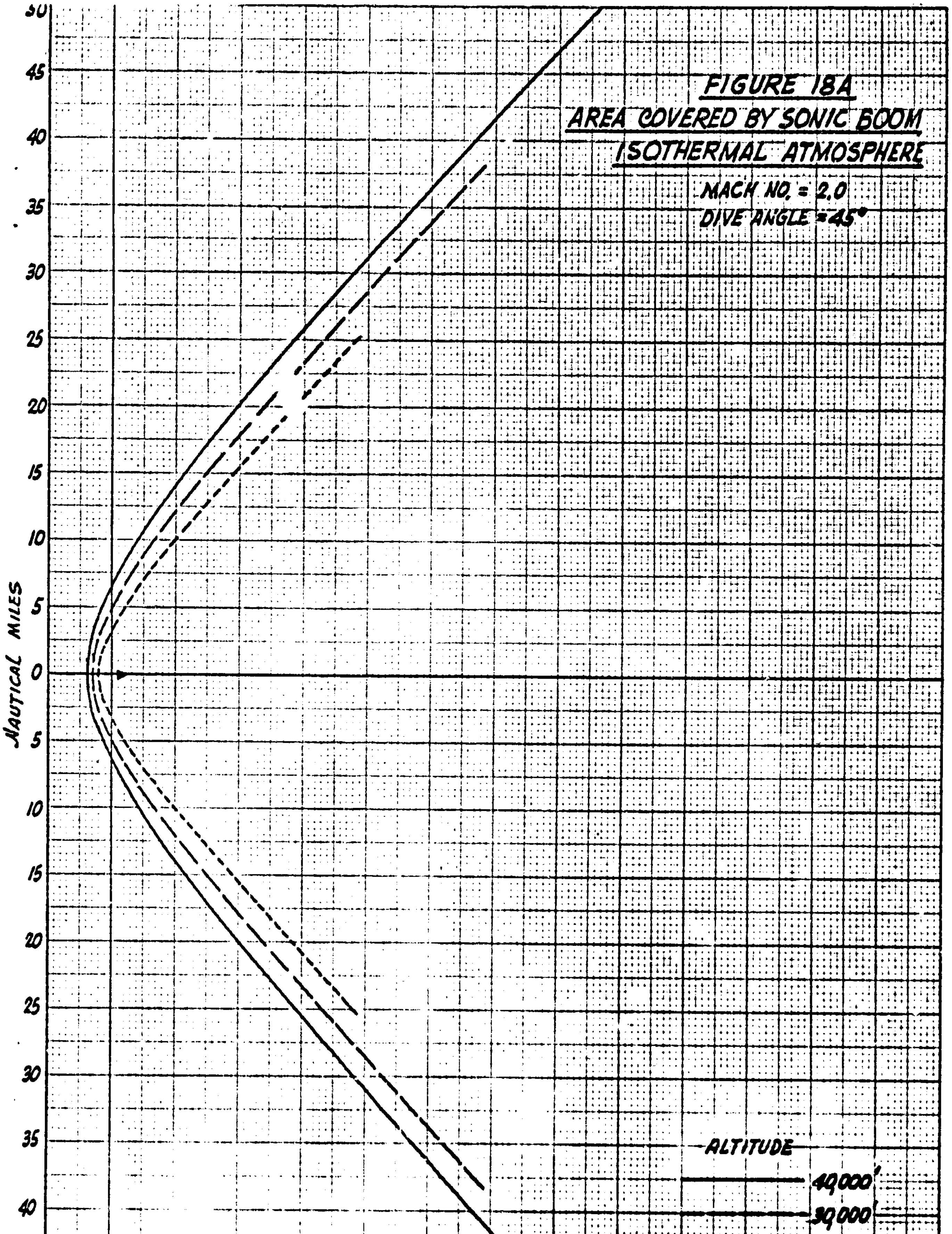


FIGURE 18A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 2.0
DIVE ANGLE = 45°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
-5
0
5
10
15
20
25
30
35
40

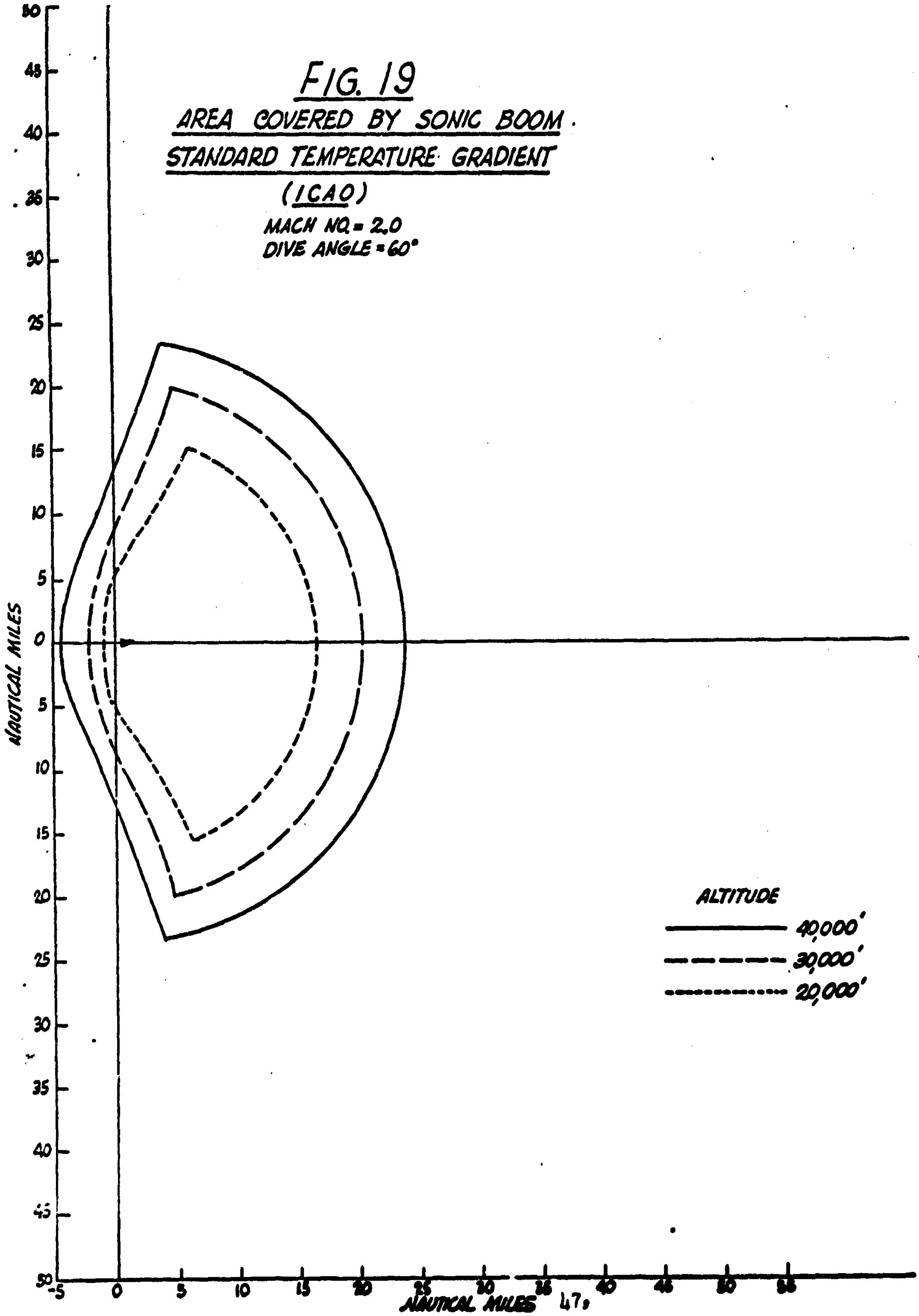
FIG. 19

AREA COVERED BY SONIC BOOM

STANDARD TEMPERATURE GRADIENT

(ICAO)

MACH NO. = 2.0
DIVE ANGLE = 60°



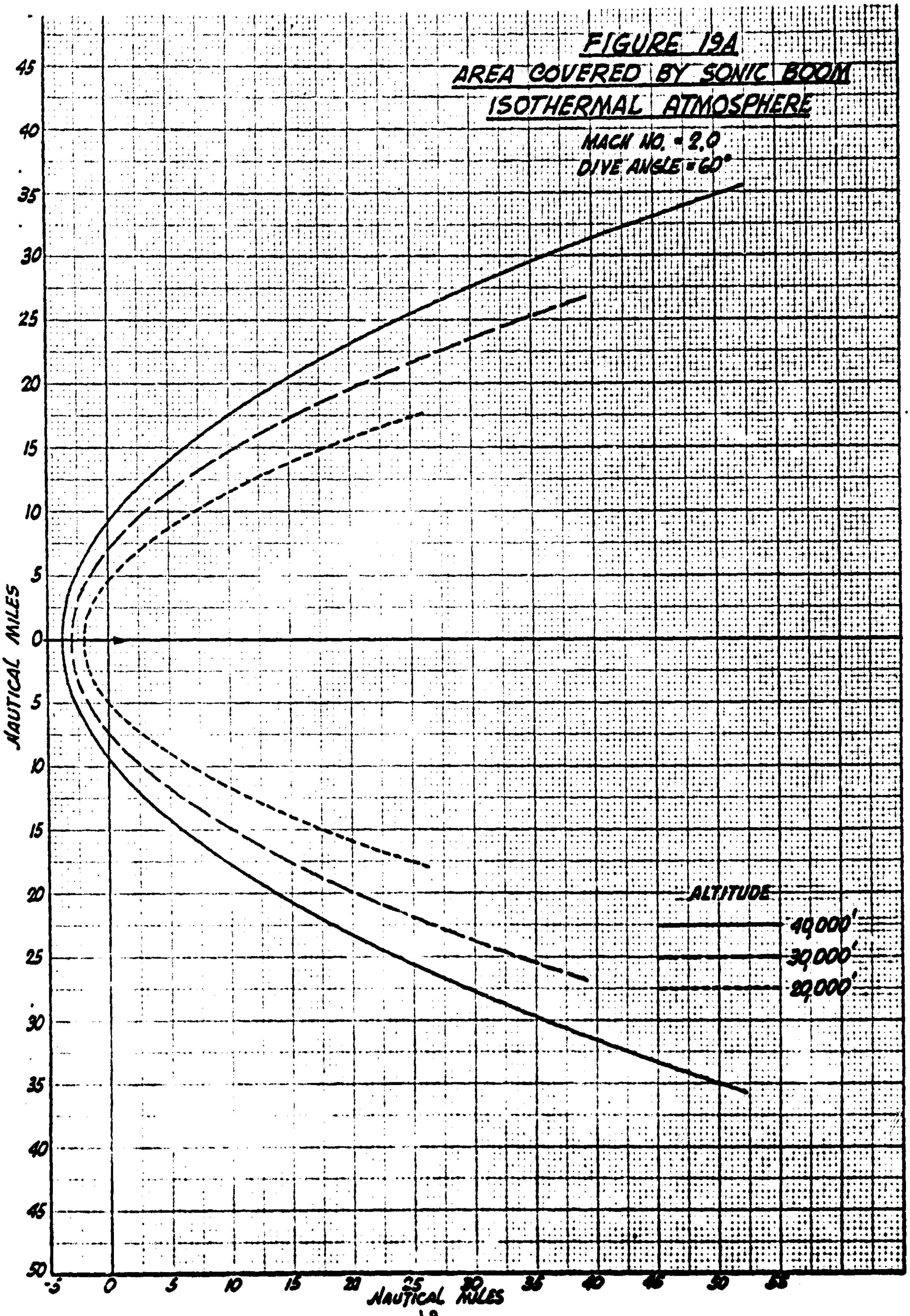


FIGURE 19A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 2.0
DIVE ANGLE = 60°
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES
NAUTICAL MILES
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
-5
0
5
10
15
20
25
30
35
40
45
50
55

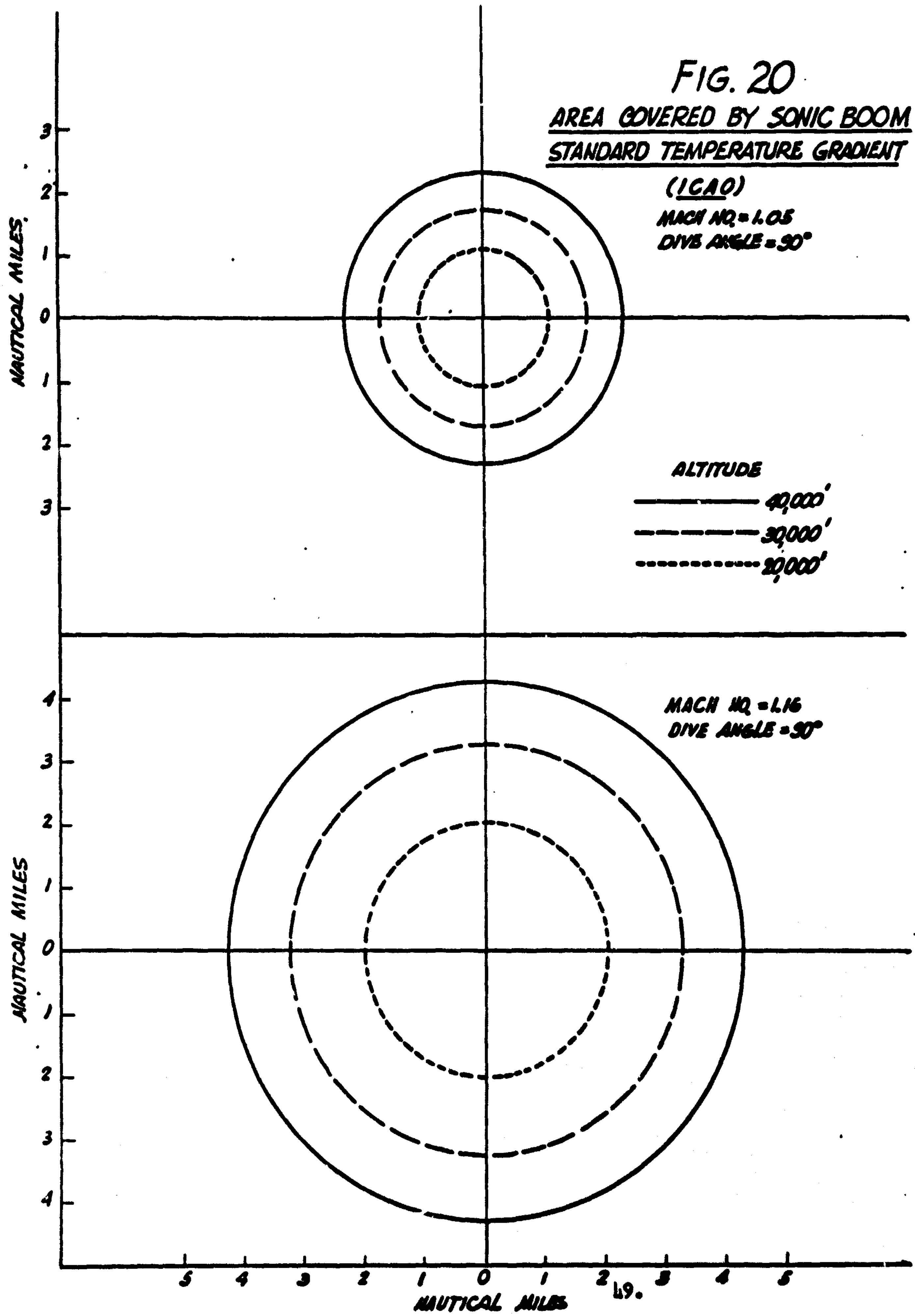


FIG. 20
AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE GRADIENT
(ICAO)

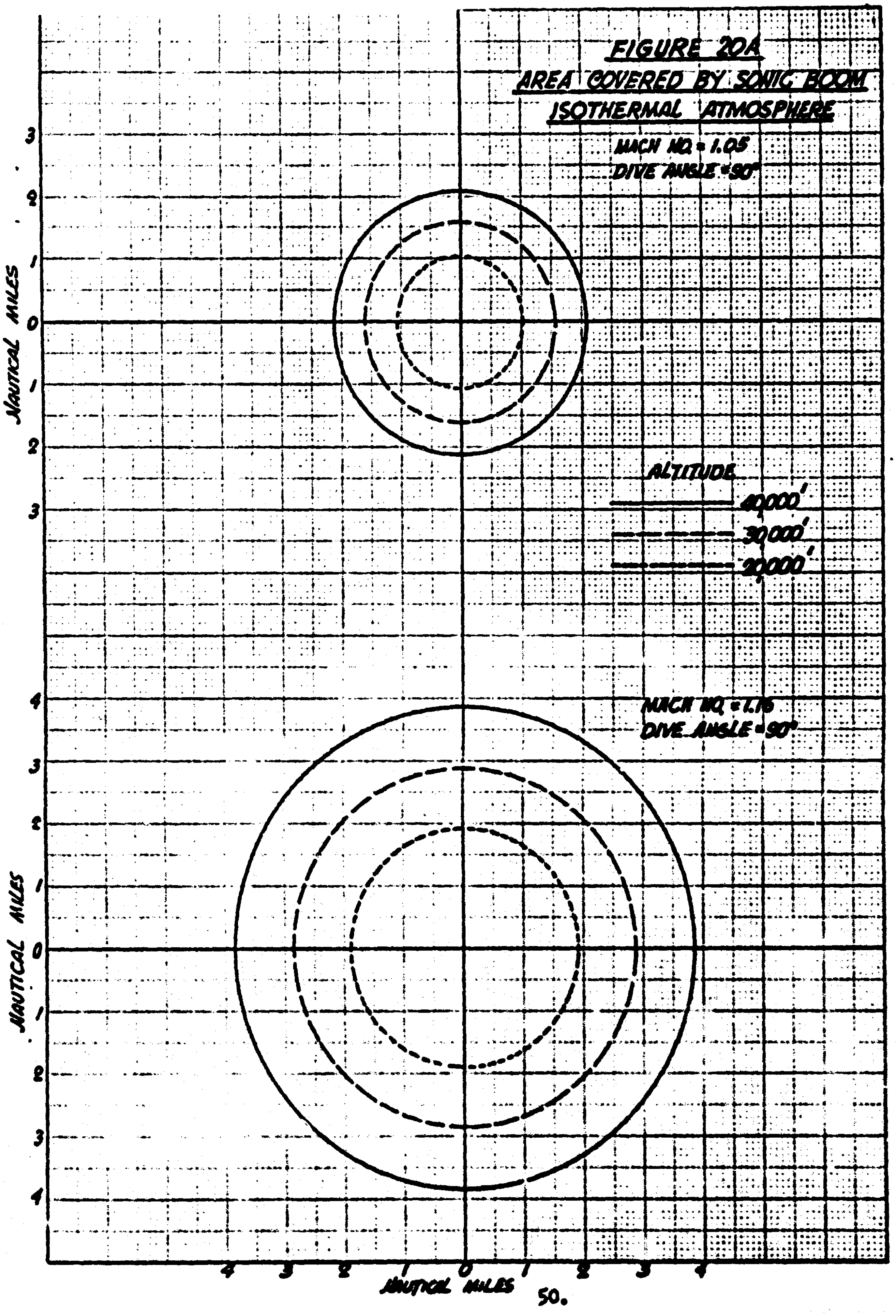
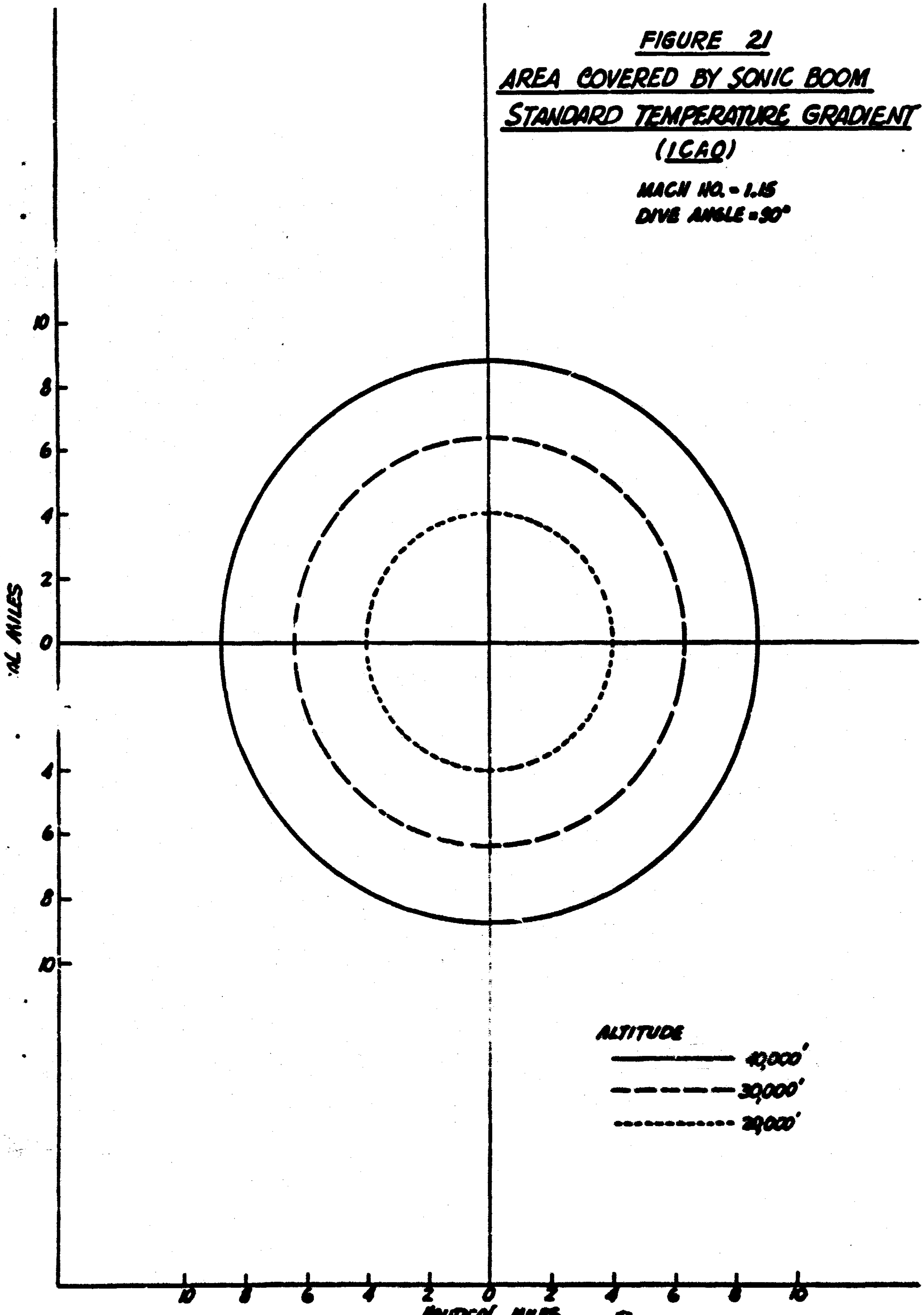


FIGURE 20A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 1.05
DIVE ANGLE = 90°
ALTITUDE
40,000'
30,000'
20,000'
MACH NO. = 1.15
DIVE ANGLE = 90°
NAUTICAL MILES
NAUTICAL MILES
NAUTICAL MILES

FIGURE 21
AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE GRADIENT
(ICAO)

MACH NO. = 1.15
DIVE ANGLE = 90°



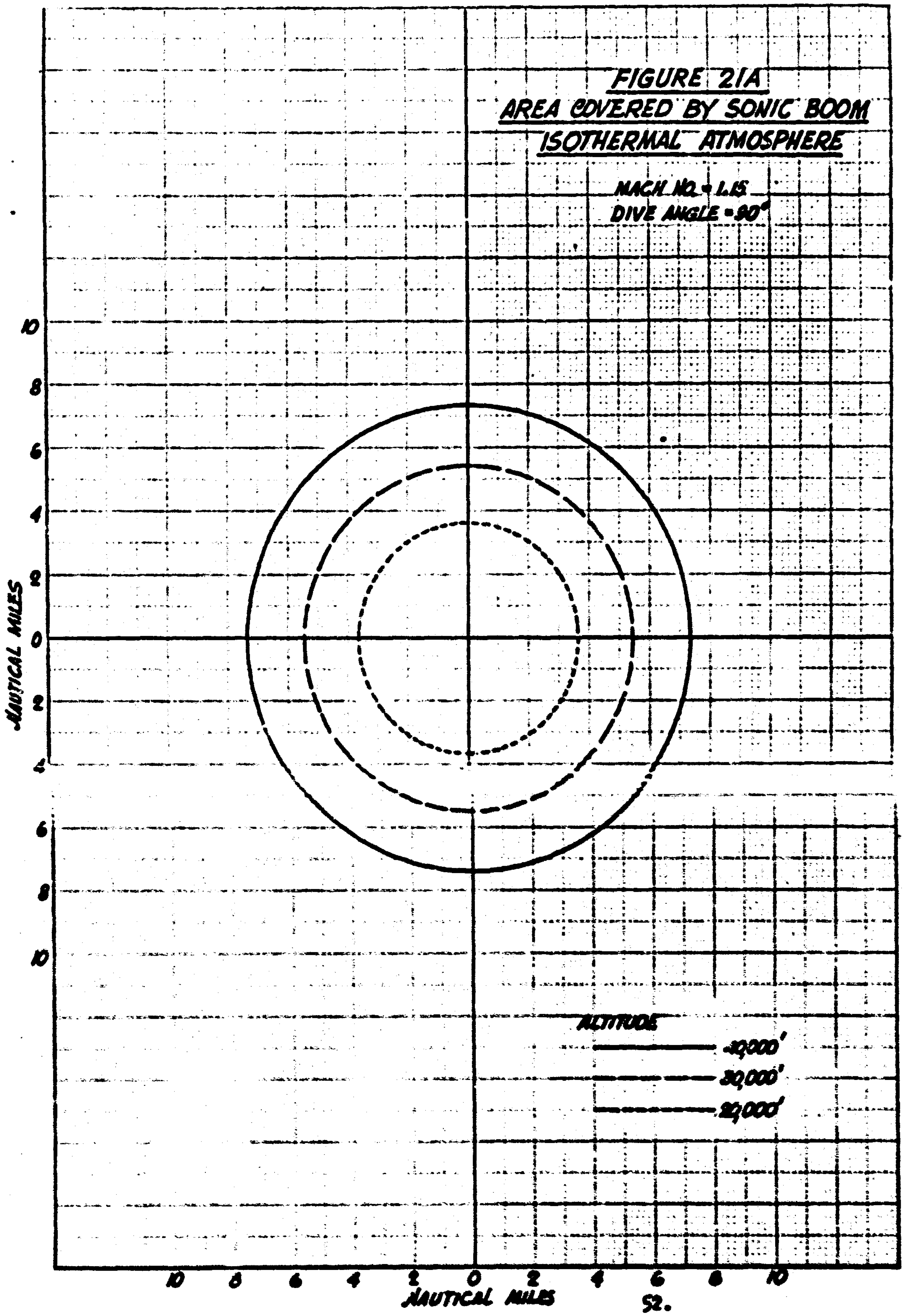


FIGURE 21A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE

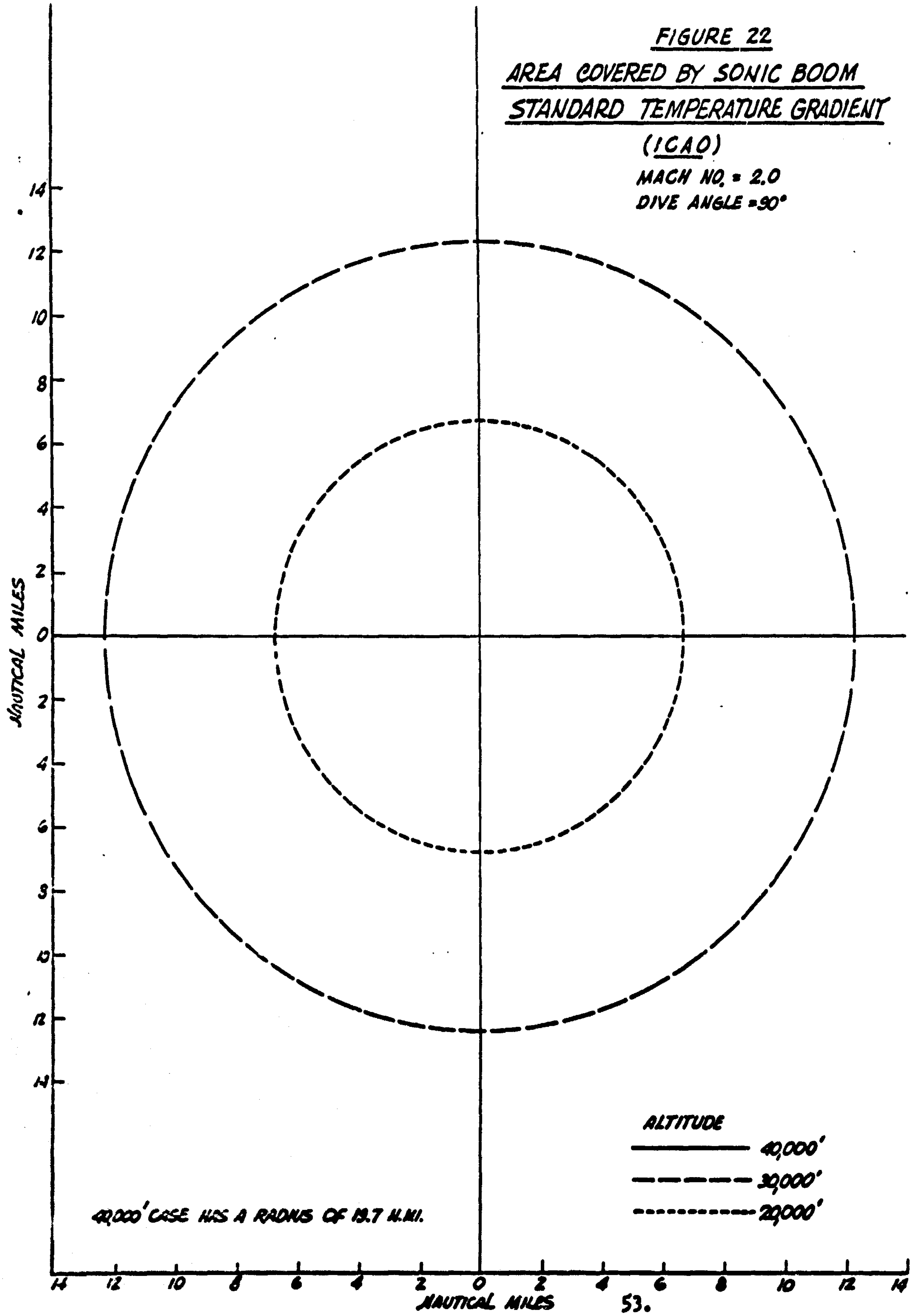


FIGURE 22
AREA COVERED BY SONIC BOOM
STANDARD TEMPERATURE GRADIENT
(ICAO)
MACH NO. = 2.0
DIVE ANGLE = 90°
NAUTICAL MILES
ALTITUDE
40,000'
30,000'
20,000'
40,000' CASE HAS A RADIUS OF 19.7 N.MI.
NAUTICAL MILES

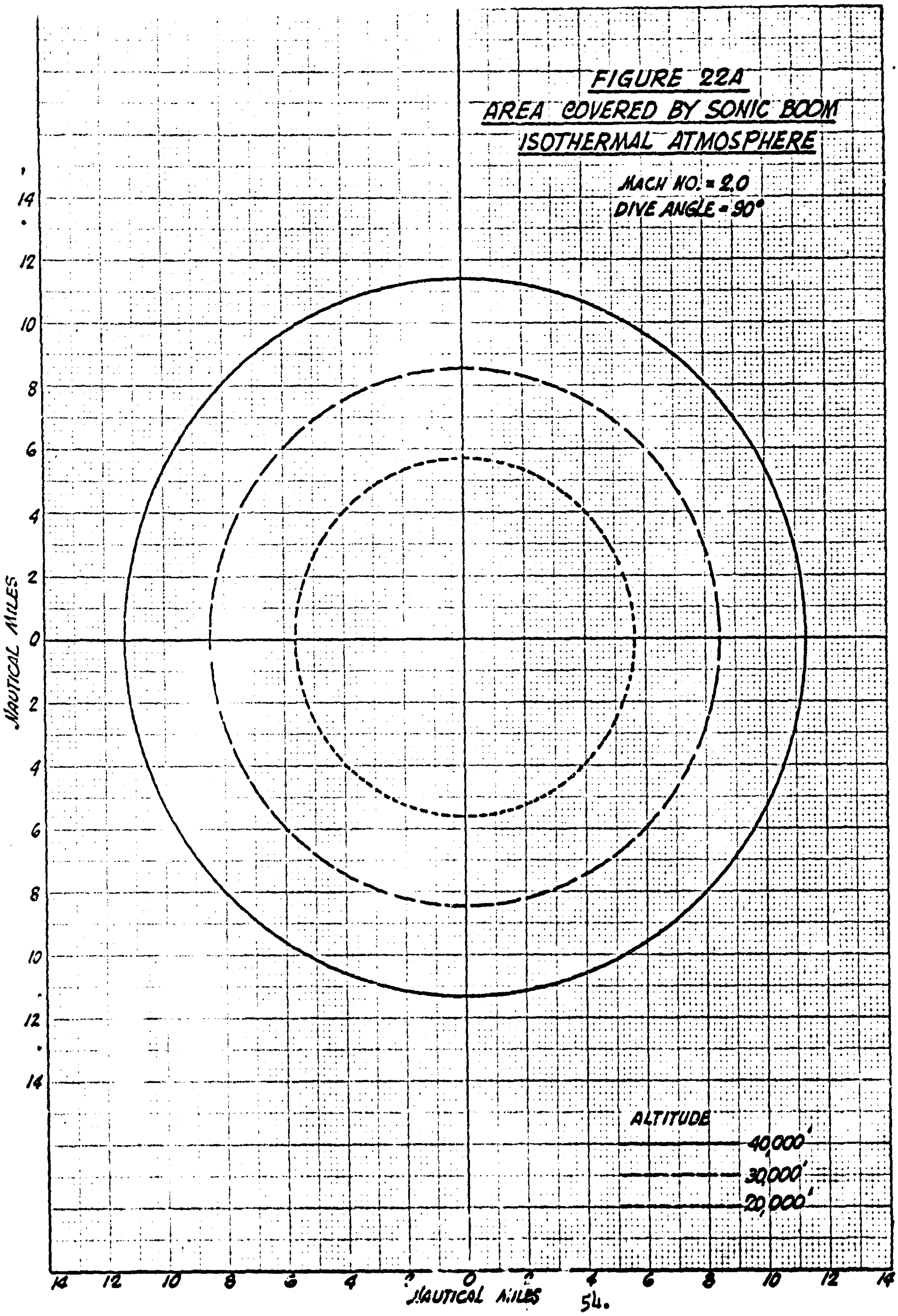
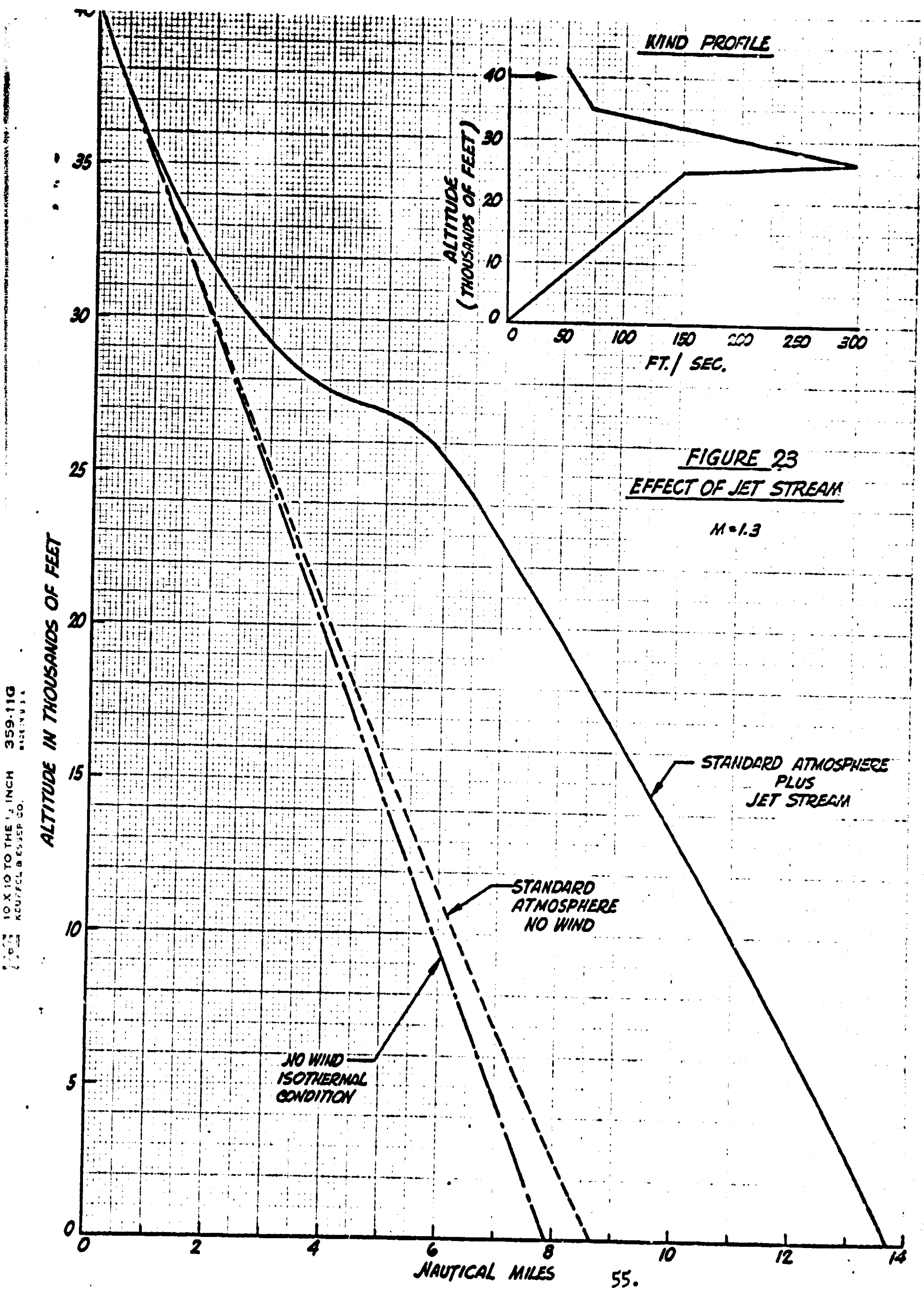


FIGURE 22A
AREA COVERED BY SONIC BOOM
ISOTHERMAL ATMOSPHERE
MACH NO. = 2.0
DIVE ANGLE = 90°
NAUTICAL MILES
14
12
10
8
6
4
2
0
ALTITUDE
40,000'
30,000'
20,000'
NAUTICAL MILES


WIND PROFILE
ALTITUDE (THOUSANDS OF FEET)
FT./ SEC.
FIGURE 23
EFFECT OF JET STREAM
M=1.3
STANDARD ATMOSPHERE PLUS JET STREAM
STANDARD ATMOSPHERE NO WIND
NO WIND ISOTHERMAL CONDITION
ALTITUDE IN THOUSANDS OF FEET
NAUTICAL MILES
10 X 10 TO THE 1/2 INCH 359-11G
KEUFFEL & ESSER CO.